Sir W. HUGGINS and Spectroscopic Astronomy

E. W. MAUNDER, F.R.A.S

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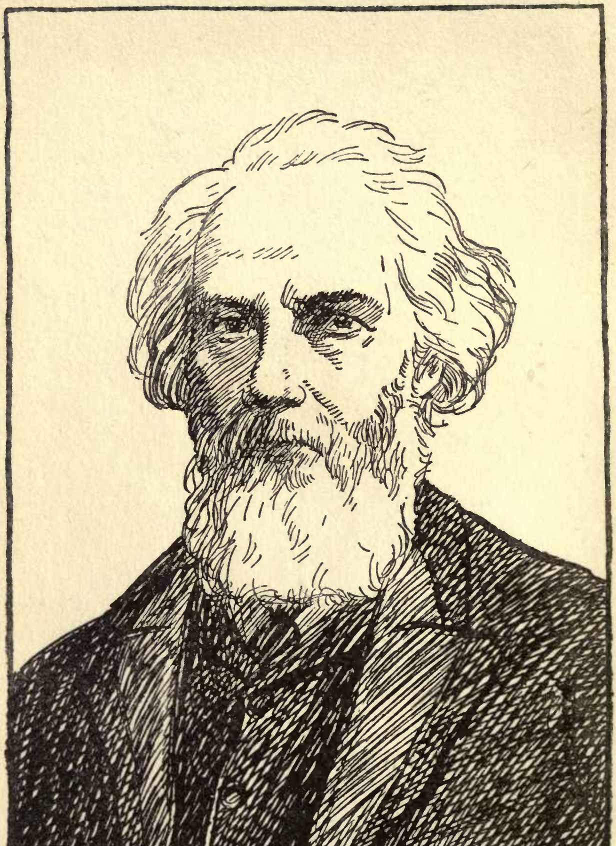

SIR WILLIAM HUGGINS AND SPECTROSCOPIC ASTRONOMY

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SIR WILLIAM HUGGINS AND SPECTROSCOPIC ASTRONOMY

CHAPTER I

THE HERSCHEL OF THE SPECTROSCOPE

SEVERAL of the volumes of this series are devoted to the biographies of eminent men, and in such a case the personality of the man himself, and the struggles through which he had to pass furnish the chief points dwelt upon. Thus Vol. XXIII gives a sketch of the life of Thomas Huxley, and, as was inevitable with such a subject, the character of the man himself as a man among men, a born fighter and controversialist, quick, resolute, fearless, is placed in vivid portraiture before the reader.

WILLIAM HUGGINS, fifteen months the senior of Huxley, was a man of an entirely different frame and disposition; not less devoted to the study of Nature, and endowed with gifts not inferior to those of his great contemporary, the path along which his inclination drew him was that of quiet persistent research, and public controversy was pre-eminently distasteful to him. For the one man, the joy of conflict furnished the crowning zest in every enterprise, without which it lacked something of the true flavour of life; to the other, dispute or contention spoiled any inquiry however attractive in itself. The greatest of all men that Science has produced—Newton—complained "Philosophy is such an

impertinently litigious lady that a man had as good be engaged in lawsuits as have to do with her," and he shrank so much from such discussions as even to contemplate giving up scientific research. "I see I have made myself a slave to philosophy, but if I get free of this present business, I will resolutely bid adieu to it eternally, except what I do for my private satisfaction or leave to come out after me; for I see a man must either resolve to put out nothing new, or to become a slave to defend it." And with his great predecessor, Huggins would have been in full agreement. The research itself, the meeting and overcoming the difficulties it presented, the patient, cautious, infinitely careful working up to stable conclusions, these were what attracted him, not the plaudits of the crowd that watch the efforts of men contending in an arena. And it must be remembered that this quiet, withdrawn, and patient work is the true Science, the thing of real value; even in the case of those, like Huxley, whose circumstances and gifts lead them into the dust and heat of controversy. Though Huggins was little more than a mere name to most of his countrymen, his work is the very type and example of scientific research;—patient and resourceful, cautious and bold, far-seeing and, above all, conscientious and exact.

WILLIAM HUGGINS was born on February 7, 1824, in London, and in 1856 he built himself an observatory at Tulse Hill, then quite out of London. Here for four or five years he made many observations of the surfaces of the sun and planets, especially of Jupiter. These early observations have been overshadowed by the great achievements of later years, but they gave evidence of many of the qualities that were to be brilliantly displayed later on.

But none of the then recognised departments of astronomical observation appealed to Huggins as offering him the sphere of activity he sought. As he himself has recorded in a retrospect in the *Nineteenth Century Review* for June, 1897:

"I soon became a little dissatisfied with the routine character of ordinary astronomical work, and in a vague way sought about in my mind for the possibility of research upon the heavens in a new direction or by new methods. It was just at this time, when a vague longing after newer methods of observation for attacking many of the problems of the heavenly bodies filled my mind, that the news reached me of Kirchhoff's great discovery of the true nature and the chemical constitution of the sun from his interpretation of the Fraunhofer lines.

"This news was to me like the coming upon a spring of water in a dry and thirsty land. Here at last presented itself the very order of work for which in an indefinite way I was looking —namely, to extend his novel methods of research upon the sun to the other heavenly bodies. A feeling as of inspiration seized me: I felt as if I had it now in my power to lift a veil which had never before been lifted; as if a key had been put into my hands which would unlock a door which had been regarded as for ever closed to man—the veil and door behind which lay the unknown mystery of the true nature of the heavenly bodies. This was especially work for which I was to a great extent prepared, from being already familiar with the chief methods of chemical and physical research."

To extend by means of the spectroscope the work that Kirchhoff had begun, from the sun to every class of luminary that the heavens present—this was the idea that filled the mind of Huggins, the enterprise to which he forthwith devoted himself for nearly half a century. The fundamental principle of the new research was not his, but it was peculiarly his to see in how many new directions it might be applied, and to meet and overcome the enormous practical difficulties before him.

For Kirchhoff had worked upon the sun, and this supplies to us ten thousand million times the light from Sirius, the brightest of all stars; yet in some respects even sunlight was none too bright for the new method of analysis. It might well have daunted even the most sanguine to apply the spectroscope, not to the sun only, but to stars, to planets, and to fainter objects still, such as comets and nebulæ.

Yet Huggins obtained the most signal success. He

identified the presence of hydrogen, sodium, magnesium, iron, and other elements in a number of the brighter stars; he determined the character of the spectra of comets and nebulæ; he took prompt advantage of the invention of the gelatine dry plate and applied it to the new research. Prior to the invention of the spectroscope, the study of the movements of the heavenly bodies had been astronomy in the strict sense; and Bessel, the greatest astronomer of his time, had somewhat scornfully refused to recognise any other celestial research as worthy of the name; but Huggins showed how it was possible to observe the movements of heavenly bodies, not as they appear projected on the vault of the sky, but in the direction at right angles to that projection—along the radial lines which have the earth as their centre.

In almost every department of the physical study of the heavenly bodies, Huggins either led the way, or was one of the earliest and most resourceful workers, so that R. A. Proctor was justified in applying to him the title of the "Herschel of the Spectroscope." For, just as Sir William Herschel, though he neither invented the telescope nor was the first to apply it to astronomical observation, yet used it as none had used it before to "break through the barriers of the heavens," to ascertain the structure of the sidereal universe, so in his turn Huggins, who neither invented the spectroscope nor was the first to use it in astronomy, yet stamped his name and impress on almost every department of research to which it was directed.

In the following chapters, no attempt is made to set forth the life of Huggins in narrative form; he lived for his science; his life was his work. To the world in general, Huggins was little known, except as a name, held in vague regard. By his fellow-workers in Science, whatever their nationality and department of study, he was esteemed one of the few who are in the first rank. The highest position in Science in this country is the

Presidentship of the Royal Society, and that he held for five years. In 1902, when the Order of Merit was instituted by King Edward, he was chosen to be one of the twelve who were the original members of the Order. The principal national learned societies abroad, both in Europe and America, enrolled him as honorary or foreign member, and his colleagues in Science were continually referring to him for his counsel and judgment in scientific questions.

CHAPTER II

THE SOURCE OF THE RAINBOW

But what is the **Spectroscope**, of which Huggins was thus so great a master? What is the **Spectrum**, and what is meant by **Spectrum Analysis**?

Light reveals to us two properties of natural objects—their form and their colour. The form does not concern us here, but colour is of the very essence of our present inquiry.

We are apt to think of the colour of an object as something added to it, just as a painter adds his pigments to his canvas. But a little thought reveals the contrary to be the case. If we enter a photographer's dark room and close the red window, we have evidently not increased the light in the room, but diminished it; the white light was more than the red. So, too, if we watch a richly-coloured landscape during the coming on of an eclipse of the Sun, we see that as the light diminishes the objects of most vivid hue disappear, while white objects still remain visible. The colour white is more, not less, than the colour red, or the colour yellow. Something is lost to us when we fill a window, not with clear glass, but with red or green; something is lost if we colour a white wall with red or green paint.

Sir Isaac Newton was the first to prove that this is the case, and that coloured light is white light from which some element has been removed; that white light is the sum of light of all colours. He was experimenting on the properties of a **prism**; that is, of a piece of glass, triangular in section, and he found—what had indeed been known before—that a beam of white

light on passing through a prism suffers two changes, one of direction and one of character or colour. If the Sun shines through a small hole in the window shutter of a darkened room, a bright spot of light is seen to fall on the wall or floor; a spot exactly in a straight line with the opening and with the Sun; but if a prism be placed in the path of the ray, then the light is turned aside at the prism, and bent out of its former course. This is what is called the **refraction** of light: the bending it from a straight course.

But this bending is not the only change. If the original beam were received on a white screen, say a sheet of cardboard, and this screen were placed at right angles to the beam, then the spot of light would be, like its source, perfectly round. But the refracted beam makes a spot neither round nor white, but elongated and coloured; it is a strip, not a circle of light; it is red at one end, shading into yellow, green, blue, and indigo in the middle, and violet at the other end; it looks like, and indeed is, a slice cut out of the arch of a rainbow. This second change, the spreading out of the white light into a coloured streak, is known as **dispersion**, and Newton gave the name of the **Spectrum** to the many-coloured image thus produced.

From what source do these colours spring? The light entering the room is white; whence has it derived the colours? It was this question, unasked by others, that Newton set himself to solve. First, he found that light travels in a straight line after passing through a prism, as it did before entering, for the refraction, the bending, takes place at the two surfaces of the prism and there alone; at the surface where the light enters and at that where it passes out. Next, the spreading out is regular. If the screen is put close to the prism, the coloured image is short; if it is a long way off, it is lengthened out, but in the exact proportion of the greater distance of the screen; the *angular* amount of the spreading is the same in each case.

But if an aperture be made in the screen, and a

beam from the many-coloured band of light, say from the yellow region or the green, be allowed to travel further on and to pass through a second prism, this yellow or green beam will thereby suffer refraction a second time, but no further dispersion. Light from the green region will remain green, from the yellow will remain yellow, and the second prism will not cause it to take on any tint of red or violet.

From such simple experiments, Newton proved that white light is made up of light of many different colours, all travelling along the same path, and so, to our sight, indistinguishable the one from the other. But on encountering a prism, these rays of different colours are differently refracted, bent from their course in different degrees, and hence are partially separated from each other; their dispersion is due to the differences of their refraction.

The red light that comes through a photographer's window is not white light that has had red light added to it, but white light from which the blue, green and yellow elements have been stopped out The red glass is opaque to them. In like manner the red petals of a geranium add nothing to the light falling on them; on the contrary they absorb the blue, green and yellow, and reject, *i.e.*, reflect, only the red.

It is easy to reconstruct white light from the many-coloured band of the "Spectrum" by allowing it to fall on a second prism, like the first in shape and material, but placed in the reverse position. Or if the spectrum be allowed to fall upon a series of very small mirrors these can be tilted so as to reflect the particular part of the spectrum falling on each, to meet at the same point of a suitable screen. In this way it can be shown that white light can be produced by the mixture of rays from three, or even from only two, different parts of the spectrum if these are properly selected.

The Rainbow is the Spectrum seen in Nature when the Sun shines out after a shower of rain, and its light falls on a layer of the atmosphere still laden with minute

particles of moisture, the light is partly reflected from the internal surfaces of each rain-drop and partly refracted, and because refracted it also suffers dispersion; the amount of refraction is different for the different colours. Hence the observer sees the sevenfold band of colour spread out before him on part of the circumference of a circle of which he is himself the centre. This being so, the old fable that a crock of fairy gold waits him who will dig in the ground from which the foot of the Rainbow springs, is easily explained; for the man who follows the Rainbow finds it always receding from him; he is always at its centre, never where it meets the earth; it is the pursuit of the unattainable.

But the old fable has had a wonderful fulfilment in the fairyland of Science; for those who have dug to find the root of the Rainbow, the source from which it springs, have found an inexhaustible treasure; a wonderful store of information about the stars above us, and the earth under our feet; about the innermost structure of the ultimate particles of matter.

Newton distinguished seven colours in the Rainbow or spectrum: red, orange, yellow, green, blue, indigo and violet, but each of the seven melts into the next on either side without any definite limit. Piazzi Smyth raised the number to ten by placing deep-red before red, and dividing green into citron or yellowish-green, emerald or full green, and glaucous or bluish-green, and the fuller division has some advantages. But even assuming that there are but seven different colours in the spectrum, it is clear that in Newton's experiment they would overlap, for a round hole to admit the light would mean a series of round images and his spectrum was not seven times as long as it was broad. Newton appears to have recognised this, and actually tried admitting the light through a narrow slit, so as to have a series of narrow coloured images side by side, overlapping each other as little as possible. But for some reason, perhaps simply because his chief object in these

experiments was the improvement of the telescope, he failed to notice a remarkable feature that the spectrum produced in this manner is able to show. He had discovered the way in which the Rainbow was formed, but he had not discovered its Secret.

CHAPTER III

THE SECRET OF THE RAINBOW

One hundred and thirty years passed after Newton's first experiments on the spectrum before another added to his work. But in 1802, Wollaston, looking casually through a prism at a narrow opening in a window-blind, perceived that the rainbow-tinted image of the slit was crossed by several dark lines parallel to the line of opening. These he supposed to be the boundaries of the different colours, and being satisfied with this explanation, he did not push the inquiry any further. Twelve years later a German optician, Fraunhofer, turned his attention to the subject, and devised a more compact instrument for examining the spectrum than the dark room with a hole in the window-shutter. With him, as with Wollaston, the light was admitted to the prism through a narrow slit, but after passing through the prism, it was not thrown on a screen, but examined directly by means of a small telescope. Under these circumstances, Fraunhofer obtained a spectrum of great purity; the images of the slit given by rays of different refrangibility, that is refracted in different degrees, overlapped as little as possible, and from end to end of the spectrum it was crossed by hundreds of fine dark lines, each an image in negative of the slit.

Thus the solar spectrum was seen at last; seen as composed of an infinite number of colours gently graded the one to the other from a dull deep brownish-red through fiery red and glowing yellow, vivid green and restful blue, to a violet that died away into a sombre tint that may best be described as a lavender-grey. But

the whole succession of living colours were crossed and interrupted by an immense number of very thin dark lines, differing in breadth and intensity of darkness, and arranged in a fashion apparently irregular.

Fraunhofer perceived that he had opened the way to an inquiry of great importance. What caused these lines, what was their explanation, where did they take their rise? These were questions that pressed for answers, and so far as his short life and many occupations permitted him, he succeeded in obtaining them.

These dark lines were not characteristic of the spectrum of every bright body; a terrestrial substance heated up to incandescence gives all the colours of the rainbow, uninterrupted by any dark lines. Thus if a piece of iron be heated in a fire, it first becomes what we call "red-hot," and when looked at through a prism only the red end of the spectrum is seen. As the iron is heated still more strongly, it shines more brightly, but with a whiter light, and as seen through the prism, its spectrum lengthens out; the colours extend into the orange and yellow. And as the process of heating it is continued, the iron becomes at length white-hot; it shines brilliantly, and as looked at through the prism, gives the entire succession of colours from red to violet; but, unlike the Sun, its spectrum shows no interruption; there are no dark lines. And what is true of iron is true of practically all other incandescent solids; they yield continuous and uninterrupted spectra.

Fraunhofer's first work in tracing out the origin of these dark lines, called since his time the **Fraunhofer lines**, was to make a careful map of them, and he counted 574 between the red and the violet, of which number he represented 354 in his map. The principal lines he distinguished by letters of the alphabet, and determined their refrangibility. With the dispersion that he used these chief lines appear as follows: A is a thick dark line at the extreme red end of the spectrum; B is also a broad line; between the two is a cluster of several lines, called *a*; C is dark and fine; all four of

these are in the red. D is a very close pair of dark lines in the orange-yellow; E is the middle and darkest of a group in the yellowish-green; *b* a group of four dark lines where the green is more of an emerald tint; F seems to be about the boundary between green and blue; G is in a crowded cluster in the indigo; and H is a pair of bands near the limit of vision in the extreme violet.

Then, turning his attention to other sources of light, Fraunhofer found that the Moon, some of the planets, the clouds, the general sky, all of which are bright by reflecting the light of the Sun, show exactly the same lines in their spectra. The stars, with their feeble light, were more difficult of examination, but as each star was but a point in the teles ope, there was no need to pass the light through a slit; all that was required was to place a prism before the object-glass of the telescope. Observing in this way, Fraunhofer found that they did not all give the same dark lines. Some, like Arcturus, resembled the Sun very closely in the spectra that they yielded; others, like Sirius and Antares, differed from it widely, and not less widely from each other.

This was important, for it showed that the cause of the Fraunhofer lines was neither in the earth's atmosphere nor in interstellar space, but lay in the Sun or star itself, or in its immediate surroundings.

Yet this was not the case with all the dark lines and bands. Some of them were soon proved to be, not formed in or round the Sun or star, but in the atmosphere of the earth; they were **telluric** lines. For when the Sun was low down in the sky, as at rising or setting, and was therefore seen through a great thickness of atmosphere, such lines were numerous, broad and dark; as it rose higher and was looked at through a thinner stratum of atmosphere, these lines became thinner and fainter or disappeared altogether. And though the spectra of Sirius or Vega when high in the heavens were quite unlike that of the Sun, the lines that came into them when they approached the horizon were just the same as those that under the same condition invaded

the solar spectrum. After Fraunhofer's death in 1826 at the age of thirty-nine, Brewster and Gladstone made a careful map of these telluric lines.

Some of the lines in the solar spectrum had been explained, but the great majority, all those indeed that truly belonged to the Sun, still remained without any clue to their meaning; they were still the Secret of the Rainbow.

Fraunhofer's work was far greater than this brief outline would suggest. For one thing he measured the **wave-lengths** of many of the chief spectral lines. Light consists of wave-movements, very short and rapid; so short that 50,000 waves of green light or 40,000 of orange light are comprised in a single inch. It is indeed because white light is made up of vibrations differing in length that on passing through a prism it is decomposed into lights of different colours, *i.e.* of different wave-lengths. For if a beam of white light passes from a rare medium to one that is denser, it suffers a retardation; if from a dense medium to a rarer, the effect is the reverse. If it encounters a plate of the dense medium, and the beam of light strikes the two surfaces at right angles, no change is effected; the retardation upon entering the plate is balanced by the acceleration upon leaving it. But if the denser medium is triangular in section, and the beam strikes the two surfaces obliquely, the beam is turned from its course, and the shorter the wave-length, the more waves to an inch, the greater is the amount of the turning. Violet light being that of shortest wave-length, is refracted, or bent out of its course, the most strongly; deep-red, being that of longest wave-length, is least deviated. The different vibrations, which entered the prism *en masse* indistinguishable from each other, leave it therefore by different paths and are seen apart.

But the lights of different wave-lengths may be separated from each other, not only by passing them through a prism, but also by using a grating. This may roughly be described as a sieve for the vibrations

of light, the divisions of the grating not being very much further apart than the wave-lengths of a single vibration. The first grating made by Fraunhofer was ingenious: two long screws of very delicate pitch were screwed through two pieces of wood, so as to make a square frame, and fine wire was wound over and over the two screws between their threads; the wires were then soldered to the screws, and lastly the screws with the wooden supports, were sawn through lengthways, so that two frames, each carrying a fine wire grating, were obtained. Later Fraunhofer made a grating by ruling a piece of glass, by a fine diamond point, with a vast number of fine parallel lines at equal distances apart. Modern gratings are ruled either on glass or on speculum metal, and these latter may be either plane or concave; the number of lines to the inch being usually about 14,400, but occasionally of 10,000 or 20,000 lines.

One property of a grating is that the amount of deviation produced in any ray is a function of its wave-length, and it was from this property that Fraunhofer was able to measure the wave-lengths of the chief lines; such measures showing that the dark lines are permanent features of the solar spectrum, fixed as to their places in it; fixed, that is to say, as to their refrangibilities and the lengths of the vibrations corresponding to them.

For the edge of the great A band in the deep-red there are 33,447 waves to the inch; for the similar edge of B, 36,985; for C in the bright red, 38,701; the close pair of lines in the orange-yellow, D_1 and D_2, give 43,078 and 43,122 respectively; E in the citron-green, 48,195; F in the glaucous-green, 52,246; G in the indigo, 58,959; and H where the violet is fading into grey, 64,001. Wave-lengths are not usually expressed in this manner, though perhaps it gives the clearest idea of the minuteness of these vibrations. Usually they are expressed as being so many **tenth-metres** in length; a tenth-metre being a metre divided by 10^{10}; it is the ten-millionth part of a millimetre. This scale was adopted by ÅNGSTRÖM, who made the first great map of the **diffraction spectrum**,

that is, the spectrum as given by a grating, and hence a tenth-metre is usually known as an Ångström Unit (Å. U.). A table of 23,000 lines has been prepared by ROWLAND in which the wave-length of each is given to one-thousandth part of an Ångström Unit; those for the chief Fraunhofer lines standing as under:

A, 7594·059 B, 6867·461 C, 6563·054 D_1, 5896·154 D_2, 5890·182 E, 5270·106 F, 4861·496 G, 4307·988 H, 3968·620

The sun, then, sends us light of every conceivable wave-length from those of deep-red to lavender-grey, except for the special wave-lengths corresponding to those of the dark Fraunhofer lines. But what gives rise to these lines themselves; why is the bright spectrum of the sun broken at these points; why does the sun fail to send us light of these particular wave-lengths?

CHAPTER IV

THE STORY OF SODIUM

A FAMILIAR tale will often bear retelling if it be told from a new standpoint, and that which was well known may gather freshness from the new setting. So I am fain to hope that the story of the work of the spectroscope in the field of astronomy, familiar as it is to most, and difficult as it is to some, may, if presented in a new manner, be acceptable to the former and perhaps helpful to the latter.

The leading principle of the arrangement which I propose to adopt in the remaining chapters of this book is this: The various stages of the progress in spectroscopy have been associated with different elements. One element has furnished the key to one problem, another to another; the simplicity of one has proved of value in one difficulty; the complexity of another has been not less useful in other conditions.

To write the history of spectroscopy neither from the point of strict chronological order, which is the method of the annalist; nor by following in succession the labours of the great men who have developed the science, the method of the biographer; nor by passing in review, one by one, the various celestial bodies to which the spectroscope has been applied, the method of the astronomer, might well seem at first sight to close the way to any logical treatment. And yet I think that to call up one by one the various chemical elements which have taught us the most, and to interrogate them as to the parts which they have severally played in the working out of the science, may well have a force and simplicity

of its own, and lend a quasi-dramatic touch to the narrative.

It is hard to realise how essentially modern the whole science of spectroscopy really is. One hundred years ago this method of analysis had not been dreamed of, even in its simplest form. Yet some of its simpler phenomena must surely have been noticed. It was at one time much the custom to ornament chandeliers and candlesticks with long triangular pieces of glass which were called "lustres." The bright rainbow-coloured images which these produced when the light of the Sun or of the candles fell upon them were much admired, yet no one seems to have had any idea that these bright streaks with their regular gradations of colours—red, orange, yellow, green, blue, violet—had any significance than that of pleasing the eye with an unwonted effect. No doubt it often happened that in looking through a "lustre" at a candle-flame, it had been noticed that most bright objects when viewed in this way entirely lost their shape, every portion of their form being spread out into a rainbow-coloured streak, yet the candle-flame would show itself in perfect outline right amongst the broad band of colours. So too, when looking at the firelight, while some of the flames as seen through the lustre would lose their shape entirely in a broad confusion of bright colours, here and there a particular flame would stand out by itself, apparently quite unchanged by the effect of the prism; its shape perfectly recognisable and unaltered by any fringe of red or blue light on either edge.

If anyone at any time made this observation, then, all unknown to himself, he was watching the spectrum of one of the elements, the spectrum of Sodium.

The meaning of this appearance will be better understood if we repeat the experiment and slightly vary its conditions. For example, take three sources of light: an incandescent gas mantle, an ordinary candle flame, and a spirit lamp to which some colour and luminosity have been given by sprinkling the wick with carbonate

of soda or common salt. In all three cases one precaution must be observed ; the prism must not be held between the eye and the flame directly, but considerably to one side of the latter, the point of the prism being away from the flame. And with all three the same effect is seen ; the coloured image does not appear to lie in the direction of the flame, but in the direction of the prism. But the image is of quite a different character in the three cases. The incandescent mantle gives a coloured glow in which no resemblance to the shape of the mantle can be traced. The candle flame likewise shows all the prismatic colours in a broad stripe, unlike the candle flame in outline ; but on the coloured stripe may be seen, between the red and green, a faint yellow image of the flame, an image which becomes bright and distinct if a few grains of salt are added to the candle wick. The spirit lamp treated with carbonate of soda shows itself practically unchanged when viewed through the prism ; every detail of the flame is just as we see it when looked at direct. Apparently the only effect which the prism has had upon it is that of a seeming change in its location.

The cause of the difference in effect of the prism on these three sources of light is easily understood. The spirit lamp shines by light of only one colour ; its image is seen through the prism in that same one colour and unaltered in shape. The incandescent mantle shines by white light—every colour is represented in its light, no one preponderates. The candle flame shines by light of every colour, but one particular colour preponderates ; each colour produces its own image of the candle flame, but these, by overlapping, are confused together, and the only image that can be recognised is the one due to the excess of yellow light. In the gas-mantle, as no one colour preponderates, no image due to any one colour can be isolated from the rest, and instead of a picture of the gas mantle, there is only a broad streak of the colours of the rainbow.

If the experiment is varied so that the three sources

of light, enclosed in a metal box, shine out only through a small opening in it, in like manner we should see the shape of that opening—a round hole, a narrow straight slit, or other shape—perfectly reproduced in yellow light from the spirit lamp; in the candle flame it would be faintly seen on a broad background of prismatic colour; whilst the gas-mantle would show these colours alone without any clear sharp image of the opening through which the light is shining. But in the case of the candle flame, the yellow image of a narrow slit would be more easily recognised than that of a round hole; for with the round, the red on one side and the green on the other would overlap the yellow image more seriously than in the straight and narrow slit. To use a technical expression, the slit gives a "pure" spectrum.

The one essential portion of a **spectroscope** is a prism or some other means for making light of different colours follow different paths. A narrow slit is also required in almost every instance, but the practical efficiency of a spectroscope is immensely increased by placing a lens between the slit and the prism, and having the slit in its focus. This lens, technically called the **collimator**, renders the rays that diverge from the slit parallel as they fall on the prism. If a small telescope be now used to view the spectrum formed by the prism, the instrument may be said to be complete. Several prisms or a grating may be substituted for the single prism, and so the separating power of the spectroscope may be increased, and many accessories and refinements may be added, but no essential alteration is made in the first principle of the spectroscope.

When Fraunhofer, the first to make and use a spectroscope, observed by its means a candle flame, he noticed that it gave, not one yellow image of the slit, but two exceedingly close together. The yellow light, therefore, which preponderates in the flame is not of one kind merely, but of two, differing from each other only very slightly. This shows the importance of having a complete spectroscope with which to work, for a prism

by itself would not enable the eye to distinguish between the two images of the flame, which, though really present, are so similar and so close together, that without an extremely narrow slit and a telescope to view the spectrum, they could not be separated the one from the other.

If we repeat Fraunhofer's observation with the salt-fed spirit lamp, we see at first when the slit is wide open, only one broad yellow bright line, whose breadth roughly corresponds to that of the slit opening. As the slit is gradually closed, this bright line narrows likewise, until at length it has a distinct triple appearance, the centre portion being twice as bright as the two exterior portions. As the slit is still further narrowed, this central brighter portion becomes rapidly thinner, until at length it vanishes, and a thin hair-line of blackness separates the two bright lines. These two bright lines will each narrow further as the slit is further closed, the dark space separating them widening, since the centres of the two bright lines remain at the same distance apart throughout. It is clear that the triple appearance when the slit is wider is due to the overlapping of the two images.

That all spectra consist of series of variously coloured images of the source of light, becomes yet more apparent when a flame of richer colour than that of the salt-fed lamp is examined. If the spectroscope be turned towards the "red fire" used in theatres a great number of bright lines are seen in the red, each widening with a widening slit, and narrowing as it is closed; and changing in form if the form of slit be changed. Most of the lines seen from the "red fire" are recognised as those given by a spirit lamp fed with chloride of strontium; and as early as 1827, Sir John Herschel found one particular grouping of red lines so characteristic of the chloride of strontium, and other groupings as characteristic of other substances, that, as he expressed it, "the colours thus contributed by different objects to flame afford in many cases a ready and neat way of detecting extremely minute quantities of them." It afforded also

the means of distinguishing between flames that to the unassisted eye appeared practically identical. Thus chloride of lithium gives a flame very like that from chloride of strontium, but in the spectroscope the lithium flame gives but one red line or image of the slit, and that of strontium gives several red lines, besides a blue line whose presence would not have been suggested by the mere appearance of the flame itself. A new method of analysing substances had been originated—that of **Spectrum Analysis.**

None of these spectra, however, are so universal as that of the close pair of yellow lines seen in the candle flame or salt-fed spirit lamp; for no matter what substance is volatilised, this unmistakable pair is sure to put in an appearance more or less strongly, and it is most conspicuous when common salt or carbonate of soda, or some other compound of sodium is added to the flame, though it can be detected when, to all appearance, sodium has been carefully excluded. So much is this the case that FOX-TALBOT was driven to conclude that the ubiquitous yellow pair were due to the presence of water. More careful methods ended, however, in showing that they are really due to sodium and that their constant presence is explained, partly by the fact that sodium is more widely distributed than any had supposed, and partly by the extraordinary delicacy of the spectroscopic method of analysis; for it has been calculated that the one-two hundredth part of the millionth of a grain of sodium will reveal its presence by this unmistakable pair of lines.

As mentioned in the preceding chapter, Fraunhofer had noted in the solar spectrum a very close pair of dark lines in the orange-yellow to which he gave the letter D. He further noted that these two dark lines fell in the same part of the spectrum, and were the same distance apart as the two bright yellow lines which he had already detected in the spectrum of the candle flame, which many years later were found to be characteristic of sodium.

So the matter stood for many years. But in 1859, Kirchhoff of Heidelberg resolved to test if this alleged correspondence were perfect, and therefore he observed daylight through a Bunsen flame strongly coloured by sodium. He saw the dark D lines change into bright ones; the Bunsen flame supplying light of precisely the quality which was lacking in daylight. He then allowed direct sunlight to shine through the flame, but to his astonishment found that now the dark lines D were not changed to bright by the sodium flame, but were actually deepened in their darkness.

He pushed the experiment further, and instead of sunlight, employed the limelight in which no spectroscope, however powerful, had ever detected any dark lines. "When this light was allowed to pass through a suitable flame coloured with sodium, dark lines were seen in the spectrum in the position of the sodium lines." Instead therefore of the limelight with the sodium flame in front of it, giving a spectrum of all the colours *plus* two bright lines in the yellow, the place of the two bright lines which the sodium flame, had it been by itself, would have given, was taken by two dark lines. So far as the two D lines were concerned, he had made an artificial solar spectrum.

This experiment illustrates the three chief kinds of spectra. The limelight gave a perfectly **continuous spectrum**, generally characteristic of incandescent solid substances. The sodium flame gave a **bright-line spectrum**, generally characteristic of a glowing gas. The sodium flame, when the limelight was seen through it, gave an **absorption spectrum.**

And thus Sodium, by the extreme simplicity of its spectrum, by its almost aggressive individuality, had unlocked the mystery of the dark lines which Fraunhofer was the first to map, which for a whole generation had perplexed inquirers. We must suppose that the surface of the Sun is glowing with white light—like the limelight giving a continuous and unbroken spectrum, that is to say light of every conceivable colour—and

between us and that glowing surface there is associated with the Sun an atmosphere of glowing sodium vapour. This, could we see it by itself, would give us for its spectrum the two bright yellow lines of the salt-fed spirit lamp, but when we look at the white light of the Sun through it, it stops out or **absorbs** light of the same quality as itself it has the power to emit, so causing the continuous solar spectrum to be broken by the presence of the two dark **absorption-lines** D. Therefore Sodium, the terrestrial element with which we are so familiar here, exists likewise in the Sun, exists in the form of a glowing gas.

Since one terrestrial element has been recognised in the Sun in this manner, it has needed but to apply the same principle further in order to recognise many more.

The spectrum of Sodium, therefore, furnished the key to the significance of the dark lines of the solar spectrum, and a new science, the science of celestial chemistry, was brought into existence.

CHAPTER V

THE STORY OF HYDROGEN

THE spectrum of Sodium is of extreme simplicity and of striking individuality; a pair of bright lines, twins of golden light, so like, so close together, they are unmistakable wherever seen. The spectrum of Hydrogen is also simple, but not to the same degree.

If a **vacuum-tube** be filled with pure hydrogen gas and then exhausted until only a trace of the gas is left, and an electric current passed through it, the gas will glow with a rosy light. (The middle part of the tube is drawn out into a **capillary**, the bore of the tube being there reduced to a mere thread in breadth, and the chief light proceeds from this narrow section; the light from the broader ends of the tube does not concern us here.) This rosy or crimson light resolves itself in the spectroscope into four bright lines; the first a bright full red, the second greenish-blue, the third indigo or deep blue, the fourth violet. And corresponding to these four bright lines of hydrogen, known as Hydrogen Alpha, Beta, Gamma and Delta (α, β, γ, δ), are four of the chief dark lines in the solar spectrum. Of these two are the lines called by Fraunhofer C and F; a third is "near G" and is sometimes loosely called by that letter; the fourth was lettered by Fraunhofer as *h*.

Hydrogen, therefore, is one of the gases existing in a glowing condition above the solar photosphere. Emitting light of these four special wave-lengths itself, it has the power of absorbing light of the same quality. Hence it is opaque to these four special radiations from the solar photosphere, and looking down on the Sun through

a shell of this luminous hydrogen, light of these four qualities is intercepted and the solar spectrum yields us these four dark lines. Hydrogen as well as sodium is a solar constituent.

So far Kirchhoff had gone. It was Huggins' work to carry the same research from the Sun to the stars.

As already pointed out, the light of the Sun is immeasurably greater than that of even the brightest star. But the star has one advantage over the Sun; the former presents all its light as concentrated in the telescope to a single point of extreme minuteness while the Sun's light is spread over a broad disc, of which only a small part can be covered by the slit of the spectroscope at any one time. But this gain brings with it a serious drawback; the spectrum of a star is not a broad rainbow-coloured band, but an exceedingly narrow rainbow-coloured line, finer than a thread, too narrow for transverse lines interrupting it to be measured successfully and compared in their positions with the bright lines obtained from terrestrial elements.

Huggins overcame these difficulties by broadening the image of the star in the direction of the length of the slit, while preserving it unaltered in the transverse direction, by the use of a **cylindrical lens**; but the details of the arrangements by which he measured the exact positions of the stellar lines and caused the spectra of various terrestrial elements to be directly compared with that of the star, cannot be described in the limited area at our disposal. Suffice it to say that in conjunction with Miller, he made a detailed study in the laboratory of the spectra of nearly all the terrestrial elements, carefully computing the wave-lengths of all the lines, and then compared these with the spectra of a number of the brighter stars, line by line. He thus detected the presence in various stars of hydrogen, sodium, magnesium, calcium, and iron. In all, the spectra of about 100 of the brightest stars were thus examined.

But though the lines of hydrogen were seen in the

spectra of most stars, they were not seen in all, nor did they offer the same characteristics in all spectra in which they appeared. RUTHERFURD early pointed out that, judged by the test of the hydrogen lines, there are three chief types of star: those that show these four lines broad, diffused and dark, the only important lines in the spectrum; those where the four lines are dark but narrow, interspersed amongst a congregation of lines of other substances; and those which show no hydrogen lines at all. SECCHI, a little later, added a fourth type, and noted that a few stars do not come exactly under any of the four heads, for there are several stars in the constellation Orion with the four hydrogen lines among their chief characteristics, and yet those lines are narrow and not very dark, and there are one or two stars that show the hydrogen lines *bright* on the bright background of the spectrum. There are thus six chief types of stellar spectra, and in a general way the colour of the star itself appears to be connected with the character of the hydrogen line.

Secchi's results may be summarised as under:—

Type I. White or bluish stars. Examples: Sirius, Vega, Castor. Hydrogen lines predominant and broad, dark and diffused.

Type II. Yellow stars. Examples: the Sun, Arcturus, Capella, Pollux. Hydrogen lines dark and distinct, but not broad. Many other lines.

Type III. Orange stars. Examples: Alpha Orionis, Antares, Alpha Herculis. Hydrogen lines feeble. Spectrum crossed by fluted bands, sharp towards the violet and fading off towards the red.

Type IV. Red stars. Examples: only a few faint stars. Hydrogen lines wanting. Spectrum crossed by fluted bands, sharp towards the red and fading off towards the violet end.

Type I, Variety *a*. Example: Rigel. Hydrogen lines predominant, but narrow and not very dark. Colour of stars slightly tending to a greenish tint. *See* p. 76.

Type I, Variety *b*. Examples: Gamma Cassiopeiæ and Beta Lyræ. Hydrogen lines bright.

A striking example of this sixth class was witnessed on May 12, 1866, when a faint 9th magnitude star in the Northern Crown, since generally known as T Coronæ, suddenly attained a brightness surpassing that of a 2nd magnitude star, and then rapidly faded away till it again became of the 9th magnitude by the end of the month. On the 16th of May, when it was of about the 4th magnitude, Huggins examined its spectrum and found that in addition to a spectrum apparently of Secchi's Third Type—that of the orange stars—it showed four bright lines, two of which were the well-known red and greenish-blue lines of hydrogen, its α and β lines corresponding to the dark Fraunhofer lines C and F. Their great brightness showed that the luminous gas was hotter than the stellar surface. Many such **New Stars, or Novæ**, have been observed since, and in every case hydrogen has shown its characteristic lines, bright and glowing on the background of the star's continuous spectrum.

In the case of T Coronæ it is necessary, however, to differentiate. The continuous spectrum of the star resembled that of Secchi's Third Type, that of the orange stars; and many of these are strongly variable, and show the hydrogen lines bright at maximum. This is the case with the star Mira Ceti, which goes through its changes in eleven months, and is often 1000 times as bright at maximum as at minimum. The change in T Coronæ was twice as great as this; but no greater than some other variables show, and it may perhaps be that it should be classed with these rather than with Novæ. But in any case a change of brightness so great is evidence that both Mira Ceti and T Coronæ are bodies of a very different order from our Sun.

The four bright lines of hydrogen, in the red, greenish-blue, indigo and violet, soon showed themselves again in another connection; viz. in the immediate surround-

ings of the Sun. Total eclipses had revealed that when the Sun itself is hidden by the dark body of the Moon, a narrow rim of crimson light surrounds the Moon, and weirdly shaped **prominences** of the same tint arise from it here and there. It needed a number of eclipses to establish the point that these bright crimson "flames" belong to the Sun itself. Huggins had pointed out that if the prominences were composed of glowing gas, they would give a spectrum of bright lines, and not a continuous spectrum, and it would be possible to see them in the spectroscope even when the Sun was not eclipsed. JANSSEN, who observed the eclipse of 1868, remarked then how intense the bright lines of the prominences were, looked for them after the eclipse was over, and found that he could readily see them, and LOCKYER, observing at home in England a few weeks later, independently succeeded in finding a prominence by its bright lines. Once the method was hit upon, it was easy to do that which could not be well done in the few moments of an eclipse, to determine the exact positions of the bright lines of the prominence spectrum, and they were seen to correspond to the four dark Fraunhofer lines, C, F, "near G," and *h*; that is to the four lines of hydrogen, in the red, greenish-blue, indigo and violet; together with a beautiful golden-hued line near the dark D lines of Sodium and hence known as D_3. The **chromosphere** or shallow layer from which the prominences rise, gave the same bright lines, so that the Sun was seen to be surrounded by a shell of highly heated hydrogen, mingled with at least one other element.

A new department of observation, that of the solar prominences and chromosphere, was thus opened, and Huggins showed that a narrow slit was not necessary in their case, as the differently coloured images of a prominence would not overlap or interfere with one another. If a spectroscope of sufficient power to weaken the background of diffused sunlight from the sky was used, the slit could be opened wide, wide enough to see the entire shape of the prominence, or, if the instrument

were so arranged, to take in a wide range of the solar circumference.

Of the four familiar lines of hydrogen, its α, β, γ, and δ lines, the one in the full red, corresponding to the Fraunhofer line C, proved to be the most suitable for use in prominence work, where light was abundant, but in a faint object the easiest line to recognise was β, the one in the greenish-blue, corresponding to the Fraunhofer line F. Thus it was the first recognised in the spectra of "bright-line" stars like Gamma Cassiopeiæ, of Novæ like T Coronæ, or variable stars like Mira Ceti; though usually when instrumental power was increased, α and γ could be detected later, and even δ as well. So to the early workers with the spectroscope, the "F line," greenish-blue hydrogen, was the first to be looked for in a new field, and when Huggins examined the spectrum of Jupiter, this F line of hydrogen showed up as broader and darker than the same line in the solar spectrum. Not only so, but beside the Fraunhofer lines there was in the red a strong dark band unknown to the Sun. Vogel and afterwards Maunder examined also Saturn, and the far more difficult objects, Uranus and Neptune, and though the two latter were too faint to show the dark lines of the Fraunhofer spectrum, all yielded several dark bands of which that in the red recognised in Jupiter was one, and another was a broad dark band in the position of F. It results from this that it is highly probable that the four outer planets still emit some light of their own, for it is patent that the light which they send to us bears a very considerably higher proportion to the amount which they receive than is the case with the Moon or Mars, and yet the absorption exercised by the planet's atmosphere is manifestly much greater also.

The same F line, the greenish-blue line of hydrogen, in the spectra of the stars was put by Huggins to a most notable use. It has been said above in Chapter III, that the place of a line in the spectrum is invariable, its refrangibility, its wave-length undergoes no change.

This is the broad fact of the case, but the statement requires some qualification and correction. The wave-length of a particular radiation can be changed in effect, if not in reality, by the rapid app oach of the sources of light and the observer, whether this be due to the motion of one or both combined. For in this case, so far as the observer is concerned, the waves of light are practically shortened by his movement to meet them; and the line will have its wave-length diminished, that is its refrangibility will be increased; as compared with the same radiation, obtained from a source of light at rest with relation to the observer, it will be displaced towards the violet end of the spectrum. Conversely a movement apart of the source of light and the observer will mean a displacement towards the red.

It was Huggins who first worked out this principle and put it into practical application in order to determine the movements of the stars either towards or away from the earth; that is radially, in **the line of sight.** Motion at right angles to this direction, motion as seen projected on the vault of heaven, could be observed and measured in the telescope; but hitherto it had seemed impossible that any information as to **radial motion** could ever be obtained. For this work a very considerable dispersion is required, and hence in order that the spectrum may not be too much weakened, a telescope with a very large object-glass is needed to collect sufficient light. In Secchi's work on star-types a slit might be dispensed with, as the image of the star formed by the cylindrical lens is almost a mathematical line; but in this a narrow slit is of primary importance, for otherwise the star might shift its position, and therefore the whole spectrum, including the particular line under examination, would likewise move in one direction or the other. A similar fictitious appearance of displacement will be caused if the light from the terrestrial substance which gives the comparison spectrum does not enter the slit perfectly at right angles to it. A further difficulty arose from the fact that a very strong absorp-

tion line in the star spectrum had necessarily to be chosen for measurement, and this is apt to be broad and ill-defined at the edges. This is particularly the case with the lines of hydrogen in stars of Secchi's First Type, which offered the greatest number of subjects bright enough for the observation.

The work proved too difficult for the resources then at Huggins' command, and also for those at Greenwich, where the same research was long carried on. But the introduction of rapid dry plates rendered it possible to substitute photographic observation for direct visual work at the spectroscope, and this improvement, effected by Vogel, as will be narrated later, soon raised the method to a high degree of effectiveness.

The spectrum of Hydrogen furnished the means of classifying the stars, enabled the solar chromosphere and prominences to be studied without an eclipse, and supplied a method by which the movements of stars could be measured in the line of sight.

CHAPTER VI

THE STORY OF CARBON

A CANDLE flame, or better a gas flame fed with carbonate of soda or with common salt, gives as we have seen the simplest of spectra, the twin bright golden lines of sodium. The radiations from the bluish base of either of these flames, or better from the inner cone of a "roaring" Bunsen burner, yield in the spectroscope a vision of extreme beauty, an exquisite poem in greenish light. Nor is it merely a metaphor to speak of it as a poem, for that which renders it so charming is the faultless rhythm that is displayed, the perfectly metrical character of the succession of the bright images. The same spectrum, brighter and therefore more perfectly seen, is given (with other lines) by the carbons of the ordinary electric arc.

Three bright bands reveal themselves; the first of a delicate citron tint, the second full emerald green, and the third of a rich blue, each band beginning boldly and sharply on the side towards the red, and fading away gradually on the side towards the violet. More light, more dispersion, and a narrower slit break up each of the three bands into a succession of **flutings**—that is to say narrower bands, bright and sharp on the redward side, fading towards the violet; and reveal also two similar bands of flutings beyond the three chief bands, one in the orange-red, the other in the violet. And these flutings again can be broken up into a succession of bright lines with a most rhythmical arrangement of brightness and position.

This beautiful spectrum was first described and

measured by Swan, and it is often, for the sake of distinctness, called after him the "Swan" spectrum. For there has been long controversy as to its true origin; whether it is due to carbon itself or to some compound of carbon, and if the latter, with what other element the carbon is combined. Carbon itself gives a line spectrum, and the idea that the "Swan" spectrum is due to simple carbon is now abandoned by many, but there are still two views respecting it, one that it is the spectrum of a hydrocarbon—acetylene, the other that it is due to carbon monoxide. There is another spectrum, likewise of fluted bands, as beautiful as this "Swan" spectrum and very similar to it, that is evidently given by a compound of carbon and oxygen, either the monoxide or the dioxide. Baly, Smithells, and others who regard the "Swan spectrum" as belonging to the monoxide, naturally ascribe the second to the dioxide.

But it is the "Swan" spectrum, considered by many astronomers as that of the hydrocarbons, that is of chief interest in astronomy. It is found in two classes of objects vastly different from each other; in the one it is seen in positive as bright bands, in the other, in negative as dark absorption flutings.

The former class is that of Comets. As early as 1864, Donati was able to examine the spectrum of a comet and to ascertain that it showed three bright bands, thus proving that it shone, not by mere reflection of sunlight, but by radiance of its own. The identification of the bands fell to Huggins, who showed that they correspond to the three brightest of the beautiful "Swan" spectrum.

Not that comets never yield a continuous spectrum significant of reflected sunlight. There has been much variety in this respect, and while some comets have yielded hardly anything but the "Swan" bright bands, others have given spectra almost wholly continuous. More striking still, the two comets of 1882, both of which approached the Sun very nearly, both shone almost entirely by the light of sodium vapour when near peri-

helion, and this spectrum in the comet that came second in the year and made the nearer approach of the two, finally gave way to that of iron. Under the intense heat to which this comet was exposed, first sodium and later iron were volatilised. *See* p. 52.

The second class of objects is that of the Red Stars; the members of Secchi's Fourth Type. Their broad dark bands, sharply defined on the redward side and fading off towards the violet, were shown by Secchi, Vogel and DUNÈR to be due to the reversal of the "Swan" spectrum. Huggins would seem to have compared these stars, not with the "Swan" spectrum but with that ascribed to carbon dioxide, and hence failed to detect an identity between the two; but the agreement of the Red Star bands with those of the "Swan" spectrum has long been fully established. The Red Stars therefore give the typical cometary spectrum reversed; so far as these bands are concerned, comets yield us what we should perceive if we could see a Red Star under conditions such as give us the spectrum of the Sun's chromosphere in an eclipse.

But the compound of carbon giving rise to the "Swan" spectrum is not the only combination of carbon shown by comets. The first comet bright enough to give a photograph of its spectrum was seen in 1881, and Huggins secured a very important picture of it. The spectrum showed a continuous background, crossed by a number of the most conspicuous Fraunhofer lines, such as G, *h*, H and K. The comet, therefore, shone partly by reflecting the light of the Sun. But it also yielded a spectrum of bright lines, of which the strongest group was beyond H and K at the beginning of the ultra-violet region, and a fainter lay between *h* and G. From the measures of their positions which Huggins secured, LIVEING and DEWAR proved that "these two groups indicate the presence of cyanogen, and are not to be seen in hydrocarbons unless nitrogen is also present." Huggins pointed out that both meteoric iron and stony meteorites yield hydrogen, carbonic oxide, and nitrogen; thus the

spectroscopic examination of comets fully confirmed their association with meteors, which had been established by an altogether different class of evidence. FOWLER has further indentified bands seen in the tail of a comet with a peculiar spectrum yielded by carbonic oxide at very low pressure.

The "Swan" carbon spectrum occurs the more frequently in astronomical physics, but the second banded carbon spectrum, that of a compound with oxygen, is historically of even greater importance. For Piazzi Smyth, who was in the habit of drawing his spectra and expressing the positions of his lines on a scale of "wave-numbers to an inch," that is on the inverse scale of that of wave-lengths, made a special study and a fine map of the great green band of this beautiful spectrum, which he considered as that of carbonic oxide. This map he submitted in November 1883 to the inspection of ALEXANDER HERSCHEL, who pointed out "that the 'wave-numbers' of these lines formed two perfectly similar arithmetical series, so placed with respect to each other that the fifth line of the first series was coincident with the first of the second. Further, the ninth line of the first series showed as a close doublet, and the tenth and following lines as doublets, each slightly wider than the preceding one." It was therefore clear that the component lines of this particular band, at least, formed an harmonic series, and the discovery stimulated the search for a similar underlying law in other spectra, apparently heterogeneous and without order in their arrangement.

In the spectra of the compounds of Carbon, therefore, the "Swan" spectrum revealed itself bright in Comets, and reversed, that is dark, in Red Stars; that of cyanogen linked comets with meteors, while the spectrum of carbonic oxide yielded the first case in which an harmonic arrangement of lines was definitely recognised in the spectrum of a terrestrial substance.

CHAPTER VII

THE STORY OF IRON

AFTER Kirchhoff had made the all-important comparison of the pair of dark Fraunhofer lines, D, in the solar spectrum, with the pair of bright yellow lines given by Sodium, and had grasped the significance of the relation between them, he went on to compare the spectra of other elements with the solar dark lines. In so doing he passed from a spectrum, like that of Sodium, of the utmost simplicity to one of greater complexity, for he chose iron, that yields more than 2000 lines, irregularly distributed through all the colours from deep-red to lavender-grey. But iron is a much more refractory substance than Sodium, and the method that was suitable for its spectrum, *i.e.* feeding a spirit lamp or a Bunsen flame with a solution of some salt of the element to be examined, is no longer available. A much higher temperature can be obtained by the use of the oxy-hydrogen blow-pipe, the jet of the mixed gases being directed upon the substance which is to give the spectrum.

But the electric arc or the electric spark are in most cases more effective and more convenient. In the use of the electric arc the carbon of the positive pole may have a hole bored through it lengthways, the hole being filled with the substance under scrutiny ; or the positive carbon top may be shaped like a cup and the substance inserted little by little as required. Or, and in the case of iron in particular the method is very suitable, the poles may be made of the metal itself.

But for many purposes, spark spectra are preferred, the sparks from an induction coil being caused to pass

between points of the substance under scrutiny, or it may be between a platinum point and a solution of a salt, one or more Leyden jars usually being employed in the secondary circuit. For the illumination of gases of which the spectra are desired, it is usual to fill a "vacuum tube" with the gas. The tube is then exhausted until only a trace of the gas remains, necessarily at a low pressure, and this is submitted to the action of the discharge from a coil.

Of these three methods of procuring the bright line spectra of terrestrial elements—the flame, the arc and the spark—Kirchhoff used the last in order to volatilise iron, and directing his spectroscope towards the Sun, exposed the lower half of the slit to its light, and by means of a reflecting prism placed in front of the upper half, brought the image of the spark between the iron poles into juxtaposition with it in the field of view. In the eye-piece of the spectroscope, the solar spectrum, the long bright band of the rainbow colours, interrupted by many thousands of fine dark lines, was seen in the upper half of the field (as the telescope gave an inverted image), and in the lower half hundreds of narrow bright lines due to iron, ranged irregularly through the same succession of colours. And broadly speaking, each bright line of iron was represented in place and intensity by a dark line in the solar spectrum; the single lines by single lines, the double lines by double, broad or intense lines by lines that were broad or intense, lines that were narrow or feeble by lines that had the same characteristics. As the iron spectrum in Kirchhoff's comparison with the Fraunhofer lines gave more than 60 such coincidences, the evidence of the presence of iron in the Sun is strong indeed. But this number has been raised by later workers and more powerful instruments to more than 2000, so that more careful comparisons have immensely increased the force of Kirchhoff's original conclusion.

Of these 2000 lines of iron among the most prominent are a close pair of noble dark lines in the full green; they

occur in a crowded part of the spectrum and were distinguished by the letter E by Fraunhofer, whose attention they attracted in his pioneer work.

Beside Sodium and Iron, Kirchhoff was able to identify the presence in the solar spectrum of the lines of six metals: magnesium, calcium, nickel, barium, copper and zinc. He suspected also that cobalt was there, but failed to recognise evidence of gold, mercury, antimony, arsenic, and lithium. He also failed to recognise silver, lead, silicon, strontium, aluminium, cadmium and tin, but these, as well as cobalt, have been detected since.

It was the examination of the bright line spectra of all the principal terrestrial elements and the determination of their wave-lengths that occupied Huggins in the first years of his devotion to this new field of research, and from that he proceeded to the difficult task of confronting the dark lines in the feeble spectra of the brighter stars with these bright metallic lines, with the result of establishing that the stars also are built up of the same elements as those that form the structure of our Earth and of its Sun.

The spectra of the Sun and of the stars are therefore built up in that same way. In each we have a continuous spectrum interrupted by numerous dark lines or bands; in each the continuous spectrum proceeds from a brilliant shell that is known as the **Photosphere**, giving white light, light that is to say, of all degrees of refrangibility that the eye can perceive, while the dark lines are caused by the absorption of certain gases lying immediately above the photosphere; gases capable of emitting the very same radiations that they absorb. If the photosphere could be seen alone it would yield a spectrum like that of the limelight; all the colours from deep-red to violet and lavender-grey would be seen in their proper order and succession without any break or interruption. If the gases could be seen alone they would yield a spectrum of bright lines, lines identical in their position in the spectrum, that is in their wave-length,

their refrangibility, with the dark lines actually observed. For the solar spectrum as seen is the photospheric spectrum viewed through these gases, and therefore interrupted by dark lines due to their absorption.

And though the photosphere cannot be seen free from the absorption of the luminous gases that overlie it, yet on occasion these gases can be seen apart from the photosphere; viz. in a total eclipse of the Sun. In such eclipses, prominences and chromosphere had been repeatedly seen before the spectroscope had been applied to solar research; and after it had become a weapon of astronomical observation, it was in the eclipse of 1868 that the spectra of the prominences, bright lines due largely to hydrogen, had first been seen. So the thin stratum in the lowest part of the chromosphere, where these bright-line gases chiefly lie, reveals its spectrum for a second or two at the beginning and end of totality. Ordinarily the sky immediately round the Sun is filled with a glare due to the scattering of sunlight in the atmosphere, but as the Moon passes before the Sun this glare is cut off and the shallow shell of gases can then make its presence apparent. "The moment the Sun is hidden, through the whole length of the spectrum, in the red, the green, the violet, the bright lines flash out by hundreds and thousands, almost startlingly; as suddenly as stars from a bursting rocket-head, and as evanescent, for the whole thing is over within two or three seconds."[1]

This beautiful spectacle of the "**Flash**," as from its evanescence it has been appropriately termed, is the "sudden reversal into brightness and colour of the countless dark lines of the spectrum." The spectra of the gases that by their absorption give rise to the dark lines of the Fraunhofer spectrum are here seen in their true aspect, apart from the photosphere, as bright lines; and the stratum is therefore known as the **Reversing Layer**.

Among these lines, those of iron are very numerous and range from a height of about $1\frac{1}{2}$ seconds of arc to

[1] *The Sun*, by C. A. Young, p. 82.

rather more than twice that amount. Many other elements are also represented; some of them, such as hydrogen and calcium, rising to a height of 10″ or more and forming the chromosphere. And just as hydrogen often rises in irregular forms to immense heights from the chromosphere, forming the prominences which can be observed by means of the spectroscope without an eclipse, so from time to time the reversing layer is disturbed by violent commotions, and metallic elements like iron are carried up sufficiently high to show their bright lines without the intervention of an eclipse, and on occasion something that almost suggested a general reversal of the Fraunhofer spectrum has been thus observed at the base of a prominence, even hundreds of very short bright lines being seen. Generally, however, only a few bright lines of metals are seen in the chromosphere, but certain lines of sodium, magnesium, strontium, titanium and iron show themselves pretty readily. **Metallic eruptions**, as these outbreaks rich in metallic lines are called for the sake of distinctness, are usually violent and short-lived in their movements and changes; many of the hydr gen prominences, on the contrary, though of much greater size, are comparatively slow-moving and stable.

But these metals thus invading the chromosphere do not muster all their lines in full on such occasions; many fail to answer to the roll-call. At one time in the early history of spectroscopy, it was supposed that each element had only a single spectrum, absolutely invariable in the number of its lines, in their positions and relative brightness. Now it is known that spectra are alterable in a number of particulars according to the conditions under which they are produced; the number of lines shown may vary, their actual brightness may suffer change, and their relative brightness, their width and even to some extent their wave-length or position in the spectrum may be altered. Sir Norman Lockyer has devoted many years' work to the study in the laboratory of these changes in metallic spectra, chiefly in two

directions. Of these the first is concerned with the distinction between the **long** and the **short lines** given by a particular substance. If, say, the arc is used with the poles horizontal, and a spectroscope having its slit vertical is turned upon it, the light comes generally from all parts of the arc. But if a lens is interposed between the arc and the slit so as to form an image of the arc on the slit-plate, only the light from the part of the image of the arc that actually falls on the slit will enter the spectroscope; that is to say, only the light from a narrow section of the arc at right angles to the poles. If the core of the arc gives one set of lines and the outer stratum another, the lines belonging to the core will be short, those belonging to the outer shell will be long, and this whether they are also given by the core or not. The spark may also be used in the same way. Or the arc or spark may be arranged parallel to the slit, and an image of them formed by a lens as before. In this case, if the points between which the spark is being taken are somewhat far apart the lines due to the metal may be mere points close to the electrodes, while the lines of air or of the particular gas in which the spark is being taken extend from one electrode to the other.

The vapour of the metal under examination will naturally be densest and most highly heated close to the poles, coolest and rarest at the greatest distance from them. The long lines are therefore those given most easily by the substance under examination; they are the lines developed when the substance is present only in small quantities or when the temperature is not relatively high. There need be no surprise then, that the Sun does not show all the lines of every element; thus aluminium is chiefly represented in the solar spectrum only by two strong lines in the violet, but these are the two "longest" lines of its spark spectrum.

Again, when the spectrum of a metal as given by the arc is compared with that given by the spark, many lines are seen to be common to the two as would be expected, but the relative brightness of the lines has under-

gone a change, some being distinctly stronger in the spark. Thus Lockyer writes: "Neglecting, then, all changes at the lowest temperatures, but including the flame spectrum, four distinct temperature stages are indicated by the varying spectra of the metals; for simplicity I limit myself to iron as an example. These are—

1. The flame spectrum, consisting of a few lines and flutings only, including several well-marked lines, some of them arranged in triplets.

2. The arc spectrum, consisting, according to Rowland, of 2000 lines or more.

3. The spark spectrum, differing from the arc spectrum in the enhancement of some of the short lines and the reduced relative brightness of others.

4. A spectrum consisting of a relatively very small number of lines which are intensified in the spark." [1]

In passing from the arc spectrum of iron to that of the spark, there is a marked change in the relative intensities of the lines; some lines disappearing, many becoming feebler, others brightening, and new lines appearing. If the spark be increased in intensity, this type of change is increased likewise, so that the lines of increasing strength, the "**enhanced lines**" to use Lockyer's term, might conceivably in the sequel be the sole survivors if we could view the hottest part of the spark in complete isolation.

The spectrum of an element therefore is not invariable—always and under all conditions the same; and in strict analogy the solar spectrum suffers change in accordance with the region from which it is obtained. The spectrum of the general photosphere itself is indeed practically constant; but when that photosphere is torn apart in a **sunspot** or raised into the bright ridges of a **facula**, then other regions offer themselves for scrutiny, and with changed conditions a modification of the spectrum is observed.

[1] *Inorganic Evolution*, by Sir Norman Lockyer, p. 32.

The spectrum of a sunspot shows first of all a duller background than that of the general solar surface; the continuous spectrum is weaker, and this is more marked in the umbra than in the penumbra, just as the umbra is the least luminous part of the spot. There is apparently a *general* absorption of light over a spot.

But there is also a *selective* absorption. Many dark lines are evident, and not a few dark lines or bands come into evidence; lines that are either entirely absent from the spectrum of the general surface, or are at least exceedingly difficult to detect there. On the other hand, some dark lines are weakened; others, amongst them those of hydrogen, are often *reversed; i.e.* they are seen as bright lines.

The spectrum of the chromosphere, as we have already seen, differs widely from that of the general surface, and yet more widely from the spectrum of a sunspot. "The long lines seen in laboratory experiments are suppressed, and the feeble lines exalted in the spectrum of the chromosphere. In the Fraunhofer spectrum, the relative intensities of the lines are quite different from those of coincident lines in the chromosphere."

"In the visible region of the spectrum, iron is represented by nearly a thousand Fraunhofer lines; in the chromosphere it has only two representatives."

"In sunspots we deal with one set of iron lines, in the chromosphere with another."[1]

Extending the same inquiry to stellar spectra, Lockyer has been able to show that the stars can be grouped according to the "enhanced lines" of iron, and of other elements that they show. Thus the most important lines seen bright in the solar chromosphere correspond to the chief "enhanced lines," and many of these again are strongly marked in the dark lines of the star Alpha Cygni.

Lockyer considers that this progressive change in the spectrum of iron from flame to arc, and arc to spark,

[1] *Inorganic Evolution*, p. 34.

is due to dissociation, *i.e.* to the break up of the metal into simpler constituents through the great increase of temperature in the changed conditions. Baly questions if the temperature of the spark should be considered so enormously hotter than that of the arc. He admits "that the simpler spectrum of the spark may be due to a simpler form of matter, as assumed by Lockyer, is very probable, but it by no means follows that temperature is the factor which aids this dissociation." [1] Others question the validity of the proof that iron is thus dissociated, but, however the progression in the form of the spectrum be explained, the beauty and importance of Lockyer's working out of this progression, and of his application of it to the comparative study of stellar spectra, remain unaltered. For the present, it may be adopted as at least a convenient hypothesis that the spark spectrum of iron represents a higher temperature than that of the arc, and that the presence of strongly marked "enhanced lines" in the spectrum of a star indicates a more fervid condition than where they are absent or relatively feeble.

The spectrum of iron figures importantly in two other departments of the "new astronomy." As soon as the introduction of rapid dry photographic plates rendered it possible to photograph stellar spectra with a sufficient dispersion, Vogel devoted himself to perfecting an instrument in which he could apply photography to the problem Huggins had attacked—the determination of the motions of stars in the line of sight by measuring the displacement of their lines. When this had been achieved, iron, by its richness in the number of its lines, presented itself as an ideal element for a comparison spectrum, and a single photograph gave, not one case only where a stellar line was confronted with its terrestrial equivalent, but scores or even hundreds, and the method, which, so long as it was confined to direct visual observation, failed to obtain success, became fertile in rich results. It has now become possible to determine

[1] *Spectroscopy*, by E. C. C. Baly.

the speed with which the Earth is travelling in its orbit, and so to ascertain the dimensions of the orbit and the Sun's distance, by observing the change in the apparent motion of a star from the time when we are moving most directly towards it, to the time when, six months later, we are moving most directly away. Further, from observations of a large number of stars, the motion in space of the solar system itself has been inferred, and CAMPBELL, from observations of 285 stars, deduces that this motion is at the rate of thirteen miles a second, and is directed towards a point in the constellation Hercules.

On one occasion, the lines of iron flashed out in the spectrum of an object very unlike Sun or stars. On September 18, 1882, COPELAND, Astronomer Royal for Scotland, watching the great comet of that year as it reached its perihelion, saw not only the bright yellow pair of sodium lines blaze out, but also six brilliant lines in the yellow and green, which proved to be coincident with six chief lines of iron. At this time the centre of the comet was only 300,000 miles from the surface of the Sun, and the temperature to which it was exposed was amply sufficient to volatilise iron. The lines were not long visible, and as the comet receded from the Sun, the lines of sodium faded out likewise. But the observation, short as it was, was sufficient to show that the comet, however filmy and ghostlike its outer structure, yet possessed an inner core rich in the metal so characteristic of one class of meteorites—iron.

The spectrum of Iron has illustrated the changes brought about in the appearance of a spectrum by increase of temperature, and has thus provided a means for grouping the stars in order of temperature. It has also furnished a most useful comparison spectrum for the determination of the rate of motion of stars in the line of sight.

CHAPTER VIII

THE STORIES OF MAGNESIUM AND TITANIUM

THE spectrum of sodium, as used by Kirchhoff, was one of great simplicity; a pair of strong lines in the orange-yellow, quite close together. The entire spectrum of sodium, as we know it now, is much richer than this, but the D lines still remain the typical lines of sodium.

Similarly the typical lines of magnesium are a strong triplet in the emerald-green, with wave-lengths at 5184, 5173, and 5168. It will be seen that the three components of the triplet, known among the dark Fraunhofer lines of the solar spectrum as b_1, b_2, and b_4, are not at equal intervals apart, but the space separating b_1 from b_2 is about double that separating b_2 from b_4. So, too, the three lines are not of equal intensity; b_1 is the strongest, b_2 somewhat less pronounced, b_4 much the weakest of the three. The letter b_3 is given in the solar spectrum to a line due to iron that intervenes between b_2 and b_4.

This pretty and striking arrangement of three strong green lines renders the spectrum of magnesium quite unmistakable whenever encountered, whether in the spectra of the Sun or stars; and the presence and strength of the *b* lines of magnesium, together with those of the D lines of sodium, form a ready index to the correspondence in type between the spectrum of a given star and that of the Sun; and as early as 1863, Huggins had confronted Aldebaran (Alpha Tauri) and Betelgeux (Alpha Orionis) with both sodium and magnesium, and found that both stars yielded the typical lines of these two metals, but that Aldebaran showed them the more

clearly. Betelgeux gave a spectrum of Secchi's Third Type, with dark shaded flutings as well as dark lines, and the *b* lines fell on one of these flutings and the D lines on another, but the origin of the flutings themselves was then unknown; they could be ascribed to neither element.

In the solar chromosphere the *b* lines of magnesium, together with the D lines of sodium, readily flash out; they are observed as regular constituents of its lower strata when these can be observed in a total eclipse of the Sun, and they are characteristic lines of those small bright violent prominences known as "metallic eruptions."

As the simple spectrum of the double lines of sodium was put into contrast with the complexity of that of iron with more than 2000 lines, so the triplet of magnesium may well be contrasted with the hundreds of lines that make up the spectrum of another metal—titanium. Titanium also, like sodium, magnesium, and iron, shows itself readily not only by dark absorption lines in the spectra of the Sun, and of stars of the solar (or Second) Type, but also in the solar chromosphere.

But these two metals have, like others, not only their elemental spectra, but their spectra as compounds. Under ordinary conditions we do not expect to see the spectra of compounds in the Sun, for its temperature is so high that compounds are dissociated there, the component elements being driven apart. But in sunspots we have regions of local differences of temperature and pressure, and there we also find local differences in the solar spectrum.

In 1880, Maunder discovered a series of broad dark lines in the spectrum of a sunspot, close to the *b* lines on the side nearer the red. These lines followed each other closely, like the lines of a fluting. But while spectra of separate lines are in general characteristic of elements, spectra of flutings are in general characteristic of compounds. Thus the two fluted spectra of carbon noted in Chapter VI are regarded by many as the spectra of its compounds with hydrogen and oxygen respectively.

In 1907, Fowler succeeded in proving that Maunder's series of broad lines or "bands" in the spectra of sunspots, was due to a compound of magnesium with hydrogen—magnesium hydride—a discovery of the utmost importance in the light that it throws on the temperature of sunspots, as it is clear that the temperature where that compound can be abundantly formed must be considerably lower than that of the solar surface in general.

Now fluted spectra are characteristic of two types of stars: of Secchi's Third Type, which may loosely be called the orange stars, in which the dark flutings are dark and sharp on the side nearer the violet, and fade gradually away in the red direction, and of Secchi's Fourth Type, the red stars, in which the dark flutings are dark and sharp on the side nearer the red, and fade gradually away in the violet direction. The latter were early seen to be the reverse of the spectrum shown by comets—the reversal, that is to say, of the "Swan" spectrum, the spectrum of a carbon compound. And in 1904, Fowler was able to show that the bands of the Third Type, the bands seen in Betelgeux, Mira Ceti, and many other stars, were due to the reversal of the spectrum of titanium oxide. Some of the flutings of the same compound have also been found in the extreme red of the spectra of sunspots. Thus these Third Type stars have been brought into continuity with the Second or Solar stars; they give evidence of the presence of the same elements as in the Sun, but at a lower temperature.

The spectra of Magnesium and Titanium have thus explained the origin of the flutings in the spectra of sunspots and of the Third Type stars, and have furnished an index of their relative temperature.

CHAPTER IX

THE STORY OF CALCIUM

WHEN Fraunhofer made his first map of the solar spectrum, he noticed, far down in the extreme violet, a pair of dark lines, or rather, a pair of broad shaded dark bands, standing like two giant pillars at the gateway of the darkness. For just beyond these bands the spectrum ceases to impress ordinary human sight, though the photographic plate is sensitive much further in this direction. These two bands are now known as the H and K lines, and are attributed to the element Calcium.

These are not the only lines of calcium in this part of the spectrum. Farther in the obscure region beyond K—the ultra-violet, as it is termed—there is another strongly-marked pair of lines, with the same intervals between the members of the pair as between H and K. On the other side of H, there is a strong single line in the indigo-blue, with a wave-length of 4227, H and K having wave-lengths of 3968 and 3934; while the pair of lines beyond K stand at 3737 and 3706. But as early as the year 1872, C. A. YOUNG, working on the spectrum of the chromosphere and prominences, was able to point out that "the selection of lines," seen bright in the chromosphere, "seems most capricious; one is taken and another is left, though belonging to the same element, of equal intensity, and close beside the first." He especially noted that while H and K are almost always observable in the chromosphere, the strong blue line, 4227, as well as the other lines of the metal, are very seldom seen. Thus while the H line was seen on

75 occasions out of 100, and the frequency of K—naturally less often seen, since it is nearer the limit of our vision—was 50, the blue line at 4227 had a frequency of only 3.

This apparently capricious selection in the spectrum of the chromosphere of a very few lines out of the many characteristic of an element, was ascribed by Lockyer to the effect of the extremely high temperature of the chromosphere. He considered that "iron, calcium, and magnesium, have probably a definite spectrum consisting of a few lines, which can only be completely produced at a temperature higher than any which is at present available in laboratory experiment." But, as the observations of Lockyer himself would suggest, there is another explanation which would account for this selection, and in 1897 Huggins gave the question a thorough examination. Using a spark of very small intensity, he found all the five above-mentioned lines of calcium, very intense; H and K being broad, and all the five lines "winged," *i.e.* with diffused fringes on both sides. This was when both electrodes were of metallic calcium. The substitution of platinum for calcium in one electrode diminished the quantity of calcium vapour present, and was accompanied by a narrowing and sharpening of the lines, particularly of 3737 and 3706. Then both electrodes were taken of platinum, and a trace of calcium was supplied by moistening them with a strong solution of calcium chloride; this made the blue line faint, while H and K lost their diffused edges, and became fairly sharp though still pretty broad. The electrodes were then repeatedly washed with pure water to remove even these slight traces of calcium, with the result that the blue line disappeared, the other four lines became narrowed and sharper, and lastly the lines at 3737 and 3706 vanished, leaving H and K quite fine sharp lines. As the spark was not altered in intensity throughout the series of experiments, it would appear that these progressive changes were due, not to increase of temperature. but

to a diminution in the quantity—that is to say, in the density—of the calcium vapour present. There could be no question of the gradual break-up of the element, and of its dissociation into simpler substances.

The lines H and K rise higher in the solar chromosphere even than the lines of hydrogen, and their appearance at various distances from the Sun's limb reproduce pretty closely the changes obtained by Huggins in these experiments so far as the breadth and diffuseness of the two lines are concerned.

Fathers Sidgreaves and Cortie at Stonyhurst have shown that the H and K lines of the general light of the Sun show at times a "**reversal**"—that is, a bright line is shown in the middle of the dark band. The Sun therefore to this extent approximates to that class of stars showing bright lines as well as dark in their spectra; it is to a small extent a "**bright-line star.**" But when an image of the Sun is formed by a telescope on the slit of the spectroscope, so that different parts of the disc can be studied in detail, such a "reversal" is very often seen. The bright line in the centre of the dark band, which is itself fairly broad, also frequently shows a further reversal, a narrow dark line being detected in its centre.

These three successive forms, say of the K line, correspond in breadth therefore to the K line as seen beyond the limb at different distances from it—that is to say, at different heights above the Sun's surface—and recall the different breadths obtained by Huggins in the experiments just cited. The narrower the line and the higher above the photosphere, the rarer we may suppose the gas to be; so that the three divisions of the line may be taken as corresponding to three different levels; the broad dark band corresponding to the reversing layer, the bright line to the chromosphere, and the narrow dark central line to its highest region.

The slit of a spectroscope allows only a narrow strip of the image of the Sun to be examined at a time; but if we remove the spectroscope while we retain the slit

and place an eye-piece behind it, we can see the whole of the Sun piecemeal, by allowing its image to drift across the slit. It would indeed be difficult to sketch the details of the Sun's surface in this way, but it would be possible to photograph them by the simple device of moving the photographic plate at precisely the same speed as the solar image was moving; or, both the image of the Sun and the sensitive plate might be fixed, and the slit might be moved at a uniform rate across both. This is, indeed, the method actually employed in the ordinary photography of the Sun. The Sun's light is so intense that even very slow plates are almost instantly fogged when they are exposed to it in a telescope; it is not possible to uncover and cover the object-glass with sufficient rapidity to get an unfogged image. A brass plate in which there is a very narrow slit is therefore placed in the focus of the telescope, cutting off all light from the sensitive plate except what comes through the slit, and this slit is drawn very rapidly across the solar image by a powerful spring. The different parts of the photographic plate are thereby *successively* exposed for a very small fraction of a second to different parts of the Sun, and a complete image of the whole Sun is built up on the plate.

Now by replacing the spectroscope behind the slit, and fixing a second slit in the plane of the spectrum so as to allow the light corresponding to one ray only to pass through, we get substantially the same arrangement, except that we confine the light used to that single radiation. As the lines of the solar spectrum are images of the first slit, if we exactly fit the second slit to one of these lines, we shut out all light except that one particular ray, and see the Sun in light of that one refrangibility or colour only; we should seem to be looking out through a single narrow slit at a Sun painted in pure monochrome, red, green, blue, or violet, according to the line chosen.

And we could photograph the entire Sun piecemeal, either by keeping the spectroscope fixed and moving

both the solar image and the photographic plate in exact accord, or by keeping the image and the plate both fixed and moving the entire spectroscope, with both its slits in a single piece across both. In both methods a complete image of the entire Sun will be built up on the plate.

This device of a spectroscope with two slits occurred to several astronomers at the same time, but G. E. HALE was the first to overcome the immense difficulties involved in its construction and employment and to make a "**spectroheliograph**," as an instrument of this kind is called, a practical success. DESLANDRES has introduced a modification of the device in order to register the rate of motion of the gas-streams over the solar surface.

The first lines selected for application to the spectroheliograph were the two giant lines of calcium, H and K; their breadth and darkness rendering them the easiest to work with; indeed Hale soon found that he could work with small portions of either line. He could set the second slit somewhere on the general broad band of K, which he distinguished as K_1, or on the bright line in its centre, K_2, or even on the very narrow dark line, K_3, which was so often seen in the centre of K_2. Each of these could in turn be isolated to give a monochromatic picture, and thus images of the Sun corresponding to three widely different levels could be obtained.

The spectroheliograph has thus not only enabled the prominences and chromosphere beyond the Sun's limb to be registered with a fulness of detail that the old laborious method of sketching each separate prominence in turn could never give, but the whole disc of the Sun has been shown to be covered by a network or mottling of bright markings to which Hale has given the name of "**flocculi.**" These flocculi have a sort of general correspondence to the bright ridges known as "faculæ," seen directly in the telescopic image of the Sun, or on ordinary photographs of it; but the spectroheliograph enables them to be photographed in all regions of the disc, even at the centre, where faculæ as ordinarily seen cannot be

traced. These flocculi are particularly bright and closely aggregated over or around sunspots; so that where the usual methods of observation will show a great group of dark sunspots, the spectroheliograph will reveal a very bright cloud of calcium vapour, the extent and brightness of which will vary according to the position on the K line, where the second slit has been placed; or we may say, in the light of Huggins' experiments on the density of calcium vapour, to the level above the solar surface to which that position of the slit will correspond.

Not all the flocculi are bright; sometimes in a complete spectroheliogram of the Sun taken in K-light, a long dark rift will show itself, and these seem closely associated with long ridges of prominences.

The invention of this particular modification of the spectroscope—the spectroheliograph—has been hardly less important than that of the spectroscope itself. It has opened up to study an entirely new field in solar physics, the study of the strata and currents of the solar atmosphere, not merely beyond the limb of the Sun, but also above the face of the disc.

The difference in the appearance of the H and K lines of calcium according as the gas is rare or condensed furnished Huggins with a means for a far more detailed classification of stellar spectra than that due to Secchi. In the spectrum of the Sun, the H and K lines form a pair, in breadth and distinctness, but in many stars the two have lost their likeness. H still remains dark, broad, and diffused while K is faint, narrow, and sharp, and it becomes an easy task to arrange those stellar spectra that agree as to the prominence of H, according to the distinctness which they give to K. Thus Regulus, Gamma Lyræ, Gamma Andromedæ, Vega, Sirius, Castor (the fainter member of the pair), Altair, Procyon, and Gamma Cygni, are all members of Secchi's First Type, showing the lines of hydrogen broad and dark. But the charts of their spectra given by Huggins in his great *Atlas of Representative Spectra* show that K is all

but invisible in Regulus, faint in Gamma Lyræ, a little more distinct in Vega and Sirius, dark, but narrow and sharp, in the fainter component of Castor, darker and broader in Altair, and a full twin to H in Procyon and Gamma Cygni. These two last-named stars approximate to Secchi's Second Type stars, with spectra like that of the Sun, wherein H and K stand out twin giants at the boundary between the violet and the invisible ultra-violet beyond. Thus within the limits of this one type of spectrum, according to Secchi's classification, there are six or seven well-marked subdivisions, capable of being arranged in unbroken orderly succession, according to the degree of distinctness with which the K line of calcium reveals itself.

The spectrum of Calcium therefore has enabled a more minute and orderly classification to be made of stellar spectra. But, above all, it has led to the invention of the spectroheliograph, and thus to the registration by photography of the distribution of the regions of varying luminosity at different heights above the solar surface.

CHAPTER X

THE SECOND STORY OF HYDROGEN

THE introduction of gelatine as a vehicle for the silver salts in photography and the supersession of the old "wet" collodion plates, by "dry plates" of far higher sensitiveness offered Huggins the means, of which he at once availed himself, for the extension of his spectroscopic researches, and he led the way in making use of the possibilities of the new process. But this involved a great alteration in the form of the instrument to be employed. If photography offered the prospect of much help, it likewise introduced many fresh difficulties, which Huggins encountered and overcame with limitless forethought, ingenuity, and patience.

Thus the eye regards one small portion of the spectrum at a time, and it can be brought to its appropriate focus while actually under observation; the photographic plate will record the spectrum as a whole, and that not merely in the visual portion, but far within the invisible ultra-violet. All this has to be brought to focus together on the plate, and the focussing must be made before the exposure begins, and must remain unchanged throughout its whole duration. Then in direct eye observation, if the star, through imperfect clock-driving of the telescope, wander off the narrow slit of the spectroscope, the observer at once sees what has happened, and brings it back by the slow-motion rod; in photographic work, such wandering would simply mean that the star would leave no image of its spectrum on the plate. This difficulty was overcome partly by the neat device of silvering the face of the slit plate and view-

ing it by a little telescope. The images of the star and of the slit were therefore seen together, and could be kept in their proper relative positions. The devotion of Lady Huggins, the unwearied assistant of her husband in all his work, did the rest, as she watched these images and guided the telescope through all the long hours of the protracted exposures required by these photographs.

In this department of stellar photography the two chief pioneers were Huggins in England and Henry Draper in the United States, and the latter was the first to secure a successful photograph of the spectrum of Vega.

Huggins had indeed obtained an impression of that of Sirius nine years earlier, but this had not showed any absorption lines; in 1876, however, Vega yielded him a most instructive negative. The visual spectrum of Vega and other stars of Secchi's First Type is crossed by four broad dark lines or bands, corresponding to the four lines of hydrogen in the red, blue-green, indigo, and violet. Huggins' photograph was not sufficiently sensitive to the red and green to bring out the first two bands, but the indigo and violet bands were strongly marked, followed by five similar bands in the ultra-violet. The entire spectrum of Vega thus displayed in all nine bands that tended to come closer and closer together the farther that they were followed into the ultra-violet, and in 1880 Huggins was able to increase the number to twelve by the addition of three more, still farther in the ultra-violet. The manifestly systematic way in which the series of lines tends to converge led Huggins to suggest that the lines must be "intimately connected with one another and present the spectrum of one substance"; and G. Johnstone Stoney decided that there could remain very little doubt that these lines were all due to hydrogen. "The evidence of their all being members of one physical system is made very plain when their positions are plotted down, for it then becomes conspicuous that they lie on, or very near, a definite curve which could not happen by chance."

Johnstone Stoney proceeded to show that the wave-lengths of several of the lines bore a simple numerical relationship to each other, but that it would be necessary to assume that some members of the series were missing. In 1885, Balmer discovered that the wave-lengths of the four hydrogen lines in the visual part of the spectrum bear a striking relation to the number 3645·6. Thus we have

Colour	*Line*	*Wave-length*	*Fraction of 3645·6*
Red	C	6562·10	9/5
Bluish-green	F	4860·74	16/12
Indigo	"near G"	4340·1	25/21
Violet	*h*	4101·2	36/32

and it became evident that the fractions could be written as :—

$$\frac{3^2}{3^2-4};\qquad \frac{4^2}{4^2-4};\qquad \frac{5^2}{5^2-4};\qquad \frac{6^2}{6^2-4}$$

or generally as $\frac{m^2}{m^2-4}$, where m is given by the integers in regular succession. As this formula, when carried on to higher values of m, was found to yield the lines observed in the ultra-violet in Vega, no doubt could be felt that they also were due to hydrogen ; nor was it long before Ames was able to produce them in the laboratory. Later, photographs of stellar spectra by Huggins and others, and of the chromospheric lines in total eclipses by Evershed, Dyson and Mitchell have enabled the series to be traced yet further still, and in all no fewer than twenty-nine lines have been observed, the fifth of which agrees very nearly in place with the H line of calcium. This explains the apparent dissimilarity between the H and K lines in certain stellar spectra ; in such cases H is really a line of hydrogen, not one of the Great Twin Brethren of calcium.

This striking discovery by which all the twenty-nine lines of hydrogen were shown to be the working out of one simple principle, soon led the way to other developments. Runge, Kayser and Paschen found the alka-

line metals, sodium, lithium, potassium, &c., give not one series of lines but three; the *Principal* series containing the lines strongest in the spectrum, and most easily reversed, while the two *Subordinate* series are distinguished from each other by the fact that one gives faint, sharp lines, the other, lines somewhat stronger but diffuse. Thus the three series may be distinguished as Principal, Diffuse and Sharp, the last two being often made up of doublets or triplets according to the element in question.

Rydberg has carried the inquiry yet further and has shown that a definite mathematical relationship exists between the three series, so that it is possible to calculate the wave-lengths of the lines in the Principal series when those in the Sharp series are known. In 1896, E. C. Pickering discovered a new series of lines in the spectrum of Zeta Puppis, a star that shows the lines of hydrogen very distinctly. But the new series bore an evident relation to the familiar series of hydrogen; indeed a slight change in Balmer's formula would give the well-known hydrogen lines when even values of m were used; *i.e.* when $m=6$, 8, 10, &c., but the new Zeta Puppis lines when the odd values, $m=11$, 13, 15, &c., were employed. Rydberg showed that this was a case of the two *Subordinate* series of one element, the familiar series belonging to the Diffuse, the new lines to the Sharp series; and from the known values of these he calculated the wave-lengths of the Principal series. This had one line in the blue at 4688, and the rest so deep down in the ultra-violet that our atmosphere prevents our tracing any astronomical spectrum so far.

In 1867, Wolf and Rayet chanced upon three small stars in Cygnus with a very remarkable spectrum, consisting both of bright and dark lines on a continuous background. Six stars more of similar character were detected in 1883 by Copeland, and since then further discoveries of the same kind have been numerous. These stars are noticeable not only for their spectra, but also for their distribution; they are found chiefly along

the very spine of the Milky Way or in the Great Magellanic Cloud, which appears to be a detached cluster of an allied nature.

The continuous spectrum of the **Wolf-Rayet stars** is traceable in fair strength into the ultra-violet. The dark absorption lines and bands which are superposed upon it are mostly of an unknown origin, the metallic elements not being represented. Hydrogen gives some of its lines as dark and some bright, and this in both series, whether the familiar Diffuse series or the Sharp series discovered by Pickering. But in the blue stands a broad bright band that is now recognised as the wanted chief line of the Principal series of hydrogen; and the same line has been photographed by MAX WOLF from the central "dark space" of the Ring nebula in Lyra. Fowler also photographed it as a high level line in the solar chromosphere during the eclipse of 1898. The same observer also obtained the line in the laboratory as at wave-length 4686 (Rydberg's calculated wave-length not being quite exact), together with its three predicted companions in the ultra-violet, and at the same time detected three members of another Principal series of hydrogen lines.

RITZ, who has carried Rydberg's inquiries as to the mathematical relationships of the wave-frequencies of the lines of elements a stage further, has computed the wave-lengths of a series of hydrogen lines occurring in the invisible portion of the spectrum beyond its less refrangible end, the "**infra-red**," as it is termed, and two of these lines have been photographed by Paschen. Thus instead of one series of lines due to hydrogen, five are now known, all closely related to each other by their mathematical formula though utterly unlike in arrangement, position in the spectrum, and appearance.

The presence in the Wolf-Rayet stars of lines characteristic of the same element, but some bright and some dark, would seem to be a question of relative temperature. A solid body, as everyone knows, as its temperature is increased, glows first with a dull red, which becomes

more vivid as the heating process is continued until at length it is white hot. If the process is watched in the spectroscope, a faint continuous spectrum is first seen far down in the deep-red which gradually gets brighter and extends further and further towards the orange, then into the yellow and green, and so on, until the object is fully white hot, and the spectrum reaches to the extreme violet. So with a glowing gas; the lines in the red show themselves strongest at the lowest temperatures, those further towards the violet become more conspicuous as the temperature is increased. In the same way the general continuous spectrum of a star will extend further into the ultra-violet and the position of its brightest region will be more in that direction the higher the temperature.

The same is observed with regard to the Sun. The red C line of hydrogen will be observed to a greater height in a prominence than the bluish-green line F, and this again will appear taller than the line "near G" in the indigo, or the *h* line in the violet. Just then, as in a spectroheliogram taken on K_3, the narrow dark line in the centre of the "reversal" of the K line is regarded as giving a view of calcium at the highest level while the edge of the broad dark K band, K_1, gives the lowest level; so a spectroheliogram on C is regarded as representing substantially a higher hydrogen level than F, and F again as higher than "near G." It is, therefore, not unnatural to find stars with "chromospheres" so hot as to give the first line of hydrogen, or even the first two as bright, while those further towards the violet remain dark.

The Wolf-Rayet stars, for all that they show this peculiarity of some lines bright and others dark from the same element, are stable in the amount of the light they radiate. But many bright-line stars are very variable; in particular the stars of Secchi's Third Type, the orange stars, with their spectra crossed by a series of dark flutings, each with a sharp dark edge on the side nearer the violet, but fading away towards the red. In

"Mira" Ceta, which may be taken as the type of these "**long period variables**," the star yields 1000 times more light at maximum that at minimum, the complete cycle of variation running its course in eleven months, and at maximum the lines of hydrogen gleam bright, but their shining appears to be confined to the lines of the violet and ultra-violet; the C and F lines do not share in the quickening of their comrades. And one of the violet lines also remains dark, the line H; but in this case Miss Clerke suggests, since the H line of hydrogen and the H line of calcium are so close to each other in position, that where either is at all broad the two overlap, that the atmosphere of Mira may contain a stratum of cooler calcium vapour, higher up than the stratum giving the bright hydrogen. On this assumption the dark H line of calcium of the upper stratum would conceal the bright H line of hydrogen from the lower.

Henry Draper has already been mentioned as a pioneer in photographing stellar spectra. His early death in 1882 put an end to the work he was carrying out with so much skill and success, but his widow, resolving to erect a suitable monument to her husband's memory, placed his telescopes at the disposal of E. C. Pickering and supplied him with ample funds to carry on, at the Harvard College Observatory, the researches in this field that her husband had commenced. In this way a great photographic survey of stellar spectra was undertaken for the northern heavens, and as far as S. Dec. 25°; 10351 stars down to the 8th magnitude being included in the "Draper Catalogue." These photographs were obtained with the simplest possible form of spectroscope, that used by Fraunhofer in his examination of stellar spectra. A prism is placed before the object glass of the photographic telescope. That is all; there is no slit, no collimator, no image formed on the slit-plate by a condensing telescope; the only two parts are the prism and the telescope for forming an image of the spectrum on the photographic plate.

Miss Maury, who examined the photographs and

classified the spectra, detected that the lines in the spectrum of Zeta Ursæ Majoris were sometimes single, sometimes double. This was true of all the lines in the spectrum, but the hydrogen lines being the strongest the fact was best exhibited by them. The cause of this change in appearance was found to be that this star, usually known as Mizar, was really a close pair, the components of which move round their common centre of gravity in a little under 21 days. At one part of their orbit therefore both stars are moving across the line of sight, and the lines are all single; at another, one star is approaching us and the other receding from us. In this case the lines of the first star are shifted, by the effect of that motion, towards the violet, the lines of the other star towards the red, and hence in the common spectrum of the two stars all the absorption lines are seen as doubled. In 1889 Miss Maury found that Beta Aurigæ, Menkalinan, showed the same effect but in a much shorter time; the swing to and fro of the lines takes place in two days, involving a revolution in four days.

Some stars, as for instance Capella, have a spectrum showing a combination of two different types; in other words, the single star that we see is really two close together but of unlike spectra. In such cases, as some lines belong entirely to one star, some entirely to the other, not all the lines are doubled, but they move relatively to each other in the compound spectrum due to the aggregate light of the two stars. In the case of Spica (Alpha Virginis), Vogel found only one spectrum visible, but from careful comparison with hydrogen, inferred that the star was sometimes receding from us and sometimes approaching us; and therefore that it must have an orbital motion round an invisible companion. So many instances of this kind have now been discovered that the Director of the Lick Observatory, on Mount Hamilton, W. W. Campbell, estimates that one star out of every five is probably a "**spectroscopic binary,**" *i.e.* a double star with only one member visible,

but the orbital motion of which is shown by these changes in its radial motion relatively to the Earth.

Sometimes a spectroscopic binary reveals its nature by the circumstance that one of the two stars is dark, and the dark member of the pair passes at times between the Earth and the bright member, thus producing a partial eclipse of its primary. The model star of this class is Algol (Beta Persei), a variable star to the naked eye, dropping every 69 hours from mag. 2·3 to mag. 3·4; thus losing three-sevenths of its light. The period of decline and recovery lasts about 9 h. 20 m.; for the remaining 60 hours the star retains its full brightness.

Goodricke, the young deaf-mute who, in 1782, rediscovered the variability of Algol, conjectured that its changes were due to an eclipsing satellite; Vogel, rather more than a century later, proved this to be the case, by showing that the bright star is moving in an orbit with a speed of more than 26 miles a second; 17 hours before minimum it recedes from us at 24 miles, 17 hours after minimum it approaches us at 28·7 miles a second; at the time of minimum, that is to say at mid-eclipse, and midway between one eclipse and the next, its motion of approach is 2·3 miles a second. From these data, the size and mass of Algol, and of its unseen companion, and their distance apart, have been computed. The diameter of Algol is more than a million miles, that of the dark companion about 830,000 miles; the distance between their centres is a little more than three million miles; and the combined masses of the two bodies amount to two-thirds that of the Sun.

Algol-type stars, so far as yet discovered, all give spectra in which metallic lines are relatively weak and inconspicuous; so that our knowledge of their movements rests chiefly on the changing displacement of the dark absorption lines due to hydrogen.

Another **short-period variable**, Beta Lyræ, is distinguished by the appearance of the lines of hydrogen in brightness, the C line glowing out like a red danger signal. Beta Lyræ is, like Algol, an eclipse variable,

but both members of the pair are bright, and as they alternately eclipse each other, there are two minima, one more marked than the other, in each period of nearly thirteen days. But the changes in the spectrum of the combined stars are most intricate and perplexing. BELOPOLSKY, however, succeeded in proving that a strong dark line in the blue at wave-length 4482, due to magnesium, belongs to one member of the system, and the bright line F of hydrogen to the other; and that the changes in the double spectra of the system go forward in a general correspondence with the changes in its aggregate brightness that follow on the alternating eclipses.

The study by photography of the spectrum of Hydrogen as given us first by the heavenly bodies, and next in the laboratory, has led to the solution of the great problem of the relations of the various lines in a given spectrum. They form definite series, calculated by formulæ of one general type, the chief constant in which is the same for all elements. Hydrogen, too, revealed the existence of a new class of binary systems — the spectroscopic doubles.

CHAPTER XI

THE STORY OF HELIUM

HELIUM, the solar element, as its name implies, was first discovered in the spectrum of the Sun; it was later, by more than half a century, that it was "run to earth." The first vague glimpse of its spectrum would seem to have been caught by MAGRINI at Milan, during the total solar eclipse of 1842, July 8. In those early days of spectrum analysis, a momentary glance through a flint glass prism at the eclipsed Sun was all that was attempted, but that glance revealed its immediate surroundings in three vivid colours—red, yellow and blue. It was not until twenty-six years later, at another solar eclipse, that of August 18, 1868, in India, that the significance of this observation was grasped. CAPT. JOHN HERSCHEL, when setting the slit of his spectroscope on a brilliant prominence, needed but to give "a single glance and the problem was solved. Three vivid lines—red, orange, blue; no others, and no trace of a continuous spectrum." The observation showed that the prominences are wholly gaseous, and are parts of the Sun. A second problem still remained as to the nature of the gas, and it was not until later, when Janssen observed the uneclipsed chromosphere, that it was found that the blue and red lines belonged to hydrogen, but that the bright yellow line was not the double D-line of sodium, but lay further towards the blue than D_2, by more than twice the distance that separated the latter from its twin brother D_1.

At first this new yellow line, D_3, was by some supposed to come from an allotropic form of hydrogen, but the

difference in its behaviour from the undoubted hydrogen lines, C and F, finally caused it to be attributed to a gas, as yet unknown, and given the name of "helium." For another quarter of a century, helium could only be examined in the Sun or in certain of the stars, until 1895 when Ramsay obtained it from the mineral clèveite. Even then its identity with solar helium was in dispute, for in the clèveite gas Runge and Paschen found that D_3 was a double not a single line, but the doubt was no sooner raised than it was set at rest by the observation, both by Huggins and by Hale, that the solar D_3 is also double.

No sooner was this settled than another question was raised for solution; whether helium was a single element, or the mixture of two elements—helium and "parhelium." At that time only one series of lines had been recognised in the spectrum of hydrogen. In the spectra of the alkalies, Kayser and Runge had found that in each case there were three distinct series—a Principal and two Subordinate series. But the gas from clèveite gave, not one series like hydrogen, nor three like lithium, but six, and of these, some were series of single lines, some of doublets. Kayser and Runge wrote: "We have accordingly here to do with six series, among which it twice happens that two series converge towards the same place. . . . Both the systems prove to have a similar appearance and all the lines of the first system are stronger than the corresponding lines of the second system. Further, it appears that both these spectra are very similar to the spectra of the alkalies. . . . We can distinguish in each of them two subordinate series diverging from the same situation, of which the brighter is the more closely spaced. Moreover, each system contains a Principal series whose lines are stronger than those of the Subordinate series, and which extends to shorter wave-lengths."[1] In *Nature* for September 26, 1895, they summed up the argument

[1] *Proc. Berlin Akad.*, June 20, 1895; *Phil. Mag.*, Sept. 1895, p. 298.

for a mixture of two elements thus : "There is no instance of an element whose spectrum contains two pairs of series ending at the same place. This suggested to us the idea that the two pairs of series belonged to different elements. . . . We therefore believe the gas in clèveite to consist of two, and not more than two constituents. We propose to call only one of the constituents helium—the one to which the bright yellow double line belongs, whose spectrum altogether is the stronger one—while the other constituent ought to receive a new name." In fact each set of three series was analogous to the complete spectrum of a distinct element. Nevertheless, not only was "parhelium" never separated from helium, but the very argument for its separate existence was turned into disproof, when it was found that oxygen also claimed six series. Hydrogen, too, has recently been shown to have two Principal series, and moreover these two are related to each other in the same manner as the Diffuse and Sharp series.

As mentioned in Chapter IX, in his report on the total solar eclipse of 1898, January 22, Fowler pointed out that there was a high level chromospheric line about wave-length 4686, which was possibly identical with the first Principal line of hydrogen, and a line of unknown origin in about the same position was shown in a photograph of the spectrum of a helium tube at the Solar Physics Observatory, South Kensington. A careful watch was kept for this line in all helium laboratory experiments, but without success until very recently it was recognised in a tube of helium prepared from clèveite in which hydrogen was the chief impurity. So far it has not been found possible to obtain the line in question from hydrogen alone under apparently identical conditions, though there is not the slightest difficulty in obtaining it when helium is also present, and it needs only a very small proportion of hydrogen to cause 4686 to show up brightly. At present it can only be said that it seems to require both hydrogen and helium to be present for this line to show up.

On Earth, helium was first derived only from clèveite and other rare mineral earths. But the study of the radio-active elements, so far as it has gone within the last few years that these substances have been recognised, has revealed one fact which is of great importance. Radium, the best known of these elements, is a metal the compounds of which resemble those of barium. But its distinctive property is that it undergoes spontaneous disintegration and decay, giving off particles of helium and a gaseous emanation which is ultimately resolved into helium and nothing else. As radium yields helium, the first term of the series of chemically inactive elements, TILDEN suggests that it seems legitimate to suppose a similar origin for neon, argon, krypton and xenon, the rare and inert gases that Ramsay discovered in our atmosphere. None of these last four elements have been observed in the spectrum of the Sun or any of the stars, but helium is, as its name implies, an important constituent of the Sun's atmosphere. But helium does not usually exhibit any absorption lines in the photospheric spectrum, though its dark lines have been seen over sunspots; it usually only manifests its presence by bright lines seen beyond the limb. Were our Sun so distant that we could examine spectroscopically neither the chromosphere nor the spots, we should not know that helium was on the Sun, though it surrounds it to a depth of 5000 miles.

Helium is, further, one of the chief constituents of gaseous nebulæ; it shows its characteristic absorption lines in stars of Secchi's First Type, Variety *a*, which are immersed in nebulæ or closely connected with them. Helium stars are not scattered indiscriminately over the heavens, but tend to congregate towards the plane of the Milky Way; indeed it is conjectured that Milky Way clusterings are largely composed of helium stars, large and small. This may not hold good in actuality but only in appearance, since the great intrinsic brightness of helium stars (which are intensely white) may leave them visible when other redder stars have

vanished through distance. For helium stars are very distant—only Regulus and Beta Centauri are within measurable distances from us.

The brightest helium star is Rigel (Beta Orionis); it is so distant that all attempts to measure the space between it and our Sun have failed, but if its proper motion be apparent only, and due to the Sun's motion in space, then its actual brightness will come out as 8000 times as great as that of Alpha Centauri, our nearest neighbour and a twin to our Sun. This great intrinsic brightness of helium stars is counted as a sign of youth and a sign of high temperature; hydrogen lines are present in helium stars, but as these "age," if we may so speak of stars, the helium lines lose their predominance as compared with those of hydrogen. And a significant characteristic of helium stars is the presence in them of the lines of the non-metals—oxygen, silicon, carbon—and the absence of metallic lines; as the metals appear the helium spectrum vanishes. Variable stars sometimes show either bright or dark helium lines and Gamma Cassiopeiae and P Cygni show both together. All "**temporary stars**" or Novæ at one stage of their evolution exhibit both helium emission and absorption.

The Orion stars were classed by Secchi with wonderful intuition, as a distinct subdivision of his First Type. This was before helium had been recognised in the Sun's chromosphere, or in stars, and long before it had been isolated in the laboratory. But his prescience was amply justified, and in Huggins' magnificent photographic *Atlas of Representative Stellar Spectra* already alluded to, the gradation of spectra is admirably brought out. Beta Lyræ, with the lines of helium bright, comes first; then follows Bellatrix (Gamma Orionis), with the helium lines dark and distinct and hydrogen narrow, and Rigel, with weaker helium and stronger hydrogen, followed by Alpha Cygni with still feebler helium absorption and hydrogen lines still narrow, and by Regulus (Alpha Leonis), where the hydrogen lines are broad and dark.

Then succeed a number of spectra of Secchi's First Type proper, with the full series of hydrogen lines dominating them all, yet with a gradual increase in the strength of the lines of the metals. The K line of calcium is seen at first as a narrow line not very strongly marked, while the H line, here a member of the hydrogen series, is broad and dark. Further spectra give instances of the gradual weakening of the hydrogen series and the strengthening of the metallic lines until H and K appear as the twin giants of the spectra of Capella, the Sun, and Arcturus, the chief representatives of Secchi's Third Type. After these comes Betelgeux (Alpha Orionis), with the calcium H and K lines less pronounced, hydrogen practically gone, and the dark flutings of titanium oxide in evidence.

The great collections of stellar spectra made at Harvard College under the classifications of Miss Maury and Miss Cannon, yield practically the same result. All the thousands of spectra examined may, with only few exceptions, be arranged in one continuous series, from the brilliantly white stars, strong in helium, a class to which the spectroscopic binaries belong, to those like Vega and Sirius where the broad lines of hydrogen predominate, then to stars where, as in the Sun, metallic lines are in chief force, and so to stars where the flutings of metallic compounds are the paramount feature.

The spectrum of Helium furnishes the first example of an element noted in an astronomical body and later recognised in the laboratory. Like hydrogen, its lines supply an apt means for the classification of stellar spectra; but unlike hydrogen it is chemically very inert. Lastly, it appears to furnish an example of the formation of one element from the disintegration of another.

CHAPTER XII

THE STORY OF NEBULIUM

"Towards the end of the last century the elder Herschel, from his observations at Slough, came very near suggesting what is doubtless the true nature, and place in the Cosmos, of the nebulæ. I will let him speak in his own words:

"A shining fluid of a nature unknown to us.

"What a field of novelty is here opened to our conceptions! . . . We may now explain that very extensive nebulosity, expanded over more than sixty degrees of the heavens, about the constellation of Orion; a luminous matter accounting much better for it than clustering stars at a distance . . .

"If this matter is self-luminous, it seems more fit to produce a star by its condensation, than to depend on the star for its existence.

"This view of the nebulæ as parts of a fiery mist out of which the heavens had been slowly fashioned, began, a little before the middle of the present century, at least in many minds, to give way before the revelations of the giant telescopes which had come into use, and especially of the telescope, six feet in diameter, constructed by the late Earl of Rosse at a cost of not less than £12,000.

"Nebula after nebula yielded, being resolved apparently into innumerable stars, as the optical power was increased; and so the opinion began to gain ground that all nebulæ may be capable of resolution into stars. According to this view, nebulæ would have to be regarded not as early stages of an evolutional progress, but rather as stellar galaxies already formed, external to our system—cosmical 'sandheaps' too remote to be sepa-

rated into their component stars. Lord Rosse himself was careful to point out that it would be unsafe from his observations to conclude that all nebulosity is but the glare of stars too remote to be resolved by our instruments. In 1858 Herbert Spencer showed clearly that, notwithstanding the Parsonstown revelations, the evidence from the observation of nebulæ up to that time was really in favour of their being early stages of an evolutional progression.

"On the evening of August 29, 1864, I directed the telescope for the first time to a planetary nebula in Draco. The reader may now be able to picture to himself to some extent the feeling of excited suspense, mingled with a degree of awe, with which, after a few moments of hesitation, I put my eye to the spectroscope. Was I not about to look into a secret place of creation?

"I looked into the spectroscope. No spectrum such as I expected. A single bright line only! At first I suspected some displacement of the prism, and that I was looking at a reflection of the illuminated slit from one of its faces. This thought was scarcely more than momentary; then the true interpretation flashed upon me. The light of the nebula was monochromatic, and so, unlike any other light I had as yet subjected to prismatic examination, could not be extended out to form a complete spectrum. After passing through the two prisms it remained concentrated into a single bright line, having a width corresponding to the width of the slit, and occupying in the instrument a position at that part of the spectrum to which its light belongs in refrangibility. A little closer looking showed two other bright lines on the side towards the blue, all the three lines being separated by intervals relatively dark.

"The riddle of the nebulæ was solved. The answer, which had come to us in the light itself, read: Not an aggregation of stars, but a luminous gas. Stars after the order of our own sun, and of the brighter stars, would give a different spectrum; the light of this nebula had clearly been emitted by a luminous gas. With an

excess of caution, at the moment I did not venture to go further than to point out that we had here to do with bodies of an order quite different from that of the stars. Further observations soon convinced me that, though the short span of human life is far too minute relatively to cosmical events for us to expect to see in succession any distinct steps in so august a process, the probability is indeed overwhelming in favour of an evolution in the past and still going on, of the heavenly hosts. A time surely existed when the matter now condensed into the sun and planets filled the whole space occupied by the solar system, in the condition of gas, which then appeared as a glowing nebula, after the order, it may be, of some now existing in the heavens. There remained no room for doubt that the nebulæ, which our telescopes reveal to us, are the early stages of long processions of cosmical events, which correspond broadly to those required by the nebular hypothesis in one or other of its forms."[1]

Such is the account given by the Master himself of the most epoch-making observation which fell even to his good fortune and skill.

In the next four years, Huggins examined spectroscopically about seventy nebulæ, and of about one-third of these he could assert that they do not yield light of many different refrangibilities and therefore do not form a continuous spectrum. These nebulæ show in the telescope a greenish tint, indeed in the case of some like the great Nebula in Orion, the green is vivid, due to its light being so largely concentrated in the line in the green at wave-length 5007, that first caught Huggins' attention in the nebula in Draco, near the pole of the ecliptic. This line has been therefore known since as the **Chief Nebular Line.** In later years W. H. Wright has extended the list of nebular lines to 19, extending from wave-length 5007 in the green to 3726 in the violet ; some of the lines being due to hydrogen, one or two to helium, and one at 3729 in the violet

[1] *Nineteenth Century Review*, June 1897.

to an unnamed substance as yet undetected on the Earth.

Not all nebulæ are of this class. The "white" nebulæ, of which the Great Nebula in Andromeda is a type, gave a very different image when a few days after this first observation, Huggins turned his spectroscope upon it. He writes: "Its light was distributed throughout the spectrum and consequently extremely faint. The brighter middle part only could be seen, though I have since proved, as I at first suggested might be the case, that the blue and the red ends are really not absent, but are not seen on account of their feebler effect upon the eye. Though continuous, the spectrum did not look uniform in brightness, but its extreme feebleness made it uncertain whether the irregularities were due to certain parts being enhanced by bright lines, or the other parts enfeebled by dark lines."[1]

But whatever the "white" nebulæ—like those in Andromeda or Canes Venatici—might be, the "green" nebulæ are certainly not groups of stars, ill-defined and irresolvable by reason of their vast distance from us; some of them are structures of a different order; they are masses of glowing gas without being condensed like our Sun, or covered by a photospheric envelope.

The Chief Nebular Line has not, as yet, been found in the spectrum of any terrestrial substance, but in the hope of such ultimate discovery the element producing it has been called Nebulium. Nor does the Sun yield any trace of it. But there is one class of star in which at one epoch of its existence the Chief Nebular Line is found. In 1876, a New Star of about the 3rd mag. appeared in the constellation Cygnus, and showed the usual bright lines of hydrogen and helium. It gradually faded and was lost to sight in the twilight in March 1877, but when it was looked for again in the following September, Copeland found that its spectrum was reduced to the bright green Chief Nebular Line. To all appearance it had been changed into a planetary nebula.

[1] *Nineteenth Century Review*, June 1897.

The next instance of a new or "temporary" star occurred in 1885, the Nova appearing in the Great Nebula in Andromeda. Spectroscopically this object yielded little information as it was only about the seventh magnitude. But in 1892 a Nova appeared in the constellation Auriga and yielded a most instructive spectrum. The lines of hydrogen, helium and calcium were bright as in the solar prominences, and each bright line was accompanied by a dark absorption line on the side nearer the violet. Huggins, in particular, was most successful in his observations of the star, whether made directly or by photography. On February 22, he obtained a photograph showing the entire hydrogen series in the violet and ultra-violet as bright lines, each with a dark absorption line beyond it. Many other bright lines were detected much further in the ultra-violet, and several of the bright hydrogen lines were seen to be double or even multiple in structure.

The star gradually faded from February 1, when it was discovered by Dr. Anderson, down to April 26, when it was only of the 16th mag. But in the following August it was re-discovered, being then of the 10th mag. Examined in the spectroscope, the experience of Nova Cygni was repeated; the spectrum was that of a planetary nebula, the Chief Nebular Line was the dominant feature, and the other bright lines were also nebular; indeed Campbell recognised nearly all the eighteen that he had measured as characteristic of planetary nebulæ.

In the following years several faint Novæ recorded themselves on the spectroscopic survey plates taken at Harvard College and were detected by Mrs. Fleming. All showed the bright prominence spectrum of Nova Aurigæ, coupled with the corresponding dark absorption lines on the side nearer the violet. But on the morning of February 22, 1901, Dr. Anderson caught a bright Nova in Perseus while it was still on the upgrade; all previous Novæ having been discovered after the moment of greatest brilliance and while declining. Photographs

of the neighbourhood showed that 28 hours earlier it must have been below the 12th mag.; now it was of the 2nd, and for the next night it was brighter than Capella.

Its spectrum was continuous at first with narrow dark lines due to helium and hydrogen, then the bright lines of both elements broke out, flanked, according to the precedent of Nova Aurigæ, by dark lines on the side towards the violet. Then as the star declined in brightness, the absorption lines faded, and the bright bands in the blue characteristic of the Wolf-Rayet stars appeared. Finally by July the Nova had taken on the nebular spectrum.

On August 22, Max Wolf obtained a direct photograph of some nebulous extensions to the Nova, which RITCHEY on September found to form a great spiral nebula encircling the star, and later photographs showed the nebula expanding in all directions at a speed that suggested that it had taken its origin at the star itself shortly before the first sudden increase in its light. Some astronomers have considered that the star was originally involved in a nebula, previously unseen, and that what had been observed was simply the successive illumination of its different parts by the light radiated from the Nova at its outburst. BARNARD is, however, clear that this theory is irreconcilable with the photographs, which testify to an actual movement of the nebulous matter.

Of three later Novæ, one discovered in Lacerta by ESPIN on December 30, 1910, and two others in Gemini, one detected in 1903, and the second in 1912, only the last-named has added to our spectroscopic information, and it has confirmed the testimony of its two great predecessors of Auriga and Perseus. All the stars of the class show a brilliant chromospheric spectrum in their first stage of decline after the outburst; that is to say the lines of hydrogen and helium, and possibly other well-known lines of the solar chromosphere, are bright. They are, however, flanked on the more refrangible side

by corresponding dark absorption lines. Many complex changes occur in the positions and characters of the lines of this double order, but eventually they fade out and give place to the bright lines typical of a planetary nebula. At this stage they can be detected in the telescope by the nearly monochromatic green image they give; at another they yield a sharp image in two quite different foci. And this is characteristic of all Novæ; at one stage, if they are viewed directly by the telescope they will give a sharp image in two quite different foci. One of these images is a bright crimson, and Barnard has pointed out that new stars can be detected as such by this crimson image for a while. But only for a while. The spectroscope shows that this crimson colour is due to the red C line of a stupendous output of hydrogen, and as the Nova fades, the hydrogen becomes less distinct and the nebular lines make their appearance.

The nature and origin of Novæ still remain unsolved. The collision of two stars, the near approach of two stars, causing a disruptive tidal wave in both, the rush of a star through a nebula have all been suggested in turn; none of the three hypotheses agree fully with all the known facts. Huggins concluded in 1893 from his observations of Nova Aurigæ, that in the outburst of these "temporary stars," "We have not to do mainly with cold matter raised suddenly to a high temperature by a collision of any form, but rather, for the most part, as was suggested by Dr. Miller and myself in 1866 in the case of the first temporary star examined with the spectroscope, with an outburst of existing hot matter from the interior of the star or stars; indeed, with phenomena broadly similar to, but on an immensely grander scale than, those with which we are familiar in the periodic greater and lesser disturbances of the Sun's surface.

"Such grand eruptions may well be expected to take place as stars cool, and if in two or more dull and comparatively cool stars such a state of things were im-

minent, then the tidal action due to their near approach might be amply adequate to determine, as by a trigger action, such eruptions.

"Under such conditions, fluctuations of brightness and subsequent partial renewals of the eruptive disturbances might well take place." [1]

This conclusion announced twenty years ago is that to which astronomers appear to be brought to-day.

But what of the gas characteristic of nebulæ, and of this final stage of Novæ? In the eighties, Lockyer made an attempt to identify the Chief Nebular Line with a "fluting" of magnesium, but Huggins was able to show that the nebular ray is slightly more refrangible than the magnesium fluting-edge, and it is sharp and fine instead of showing a one-sided haze like the fluting. We have not yet found it on the Earth, so that it cannot be analysed and weighed in the laboratory; must we relegate it to the utterly unknown?

No, for within the last two years, in a series of masterly papers communicated to the Royal Astronomical Society, J. W. Nicholson has, so to speak, outflanked the problem, and attacked it from the theoretical side. Assuming the existence of elements with the simplest possible type of atom, simpler than any yet discovered on the earth, the main conception involved in the structure of their atoms is that of the nature of positive electricity, and this is supposed to exist in small spherical volume distributions of uniform density, whose radius is small in comparison even with that of an electron, but whose mass is relatively very large. This single positive unit, with a single ring of electrons rotating in a plane round it, constitutes a "simple" atom, and he premises that an atom of nebulium, when it is electrically neutral, has a ring of four electrons, rotating uniformly in a plane circle at equal distances round a positive nucleus whose electric charge is four times that of any one electron. If the atom loses one or more electrons, the remaining electrons

[1] *Proceedings of the Royal Society*, vol. liv. p. 30, 1893.

take up equidistant positions and the atom becomes positively charged. Similarly if the atom takes up one or more additional electrons, it becomes negatively charged. These electrons form a system which rotates uniformly round the positive unit. The various periods of vibration given for the atom of nebulium when this is neutral and when it is positively and negatively charged to various degrees, are shown by Nicholson to account for 10 out of Wright's 19 nebular lines, and included in these are one at 3836 which had been hitherto attributed to hydrogen, and another at 4027, attributed to helium, while the Chief Nebular Line at 5007, is by the same means shown definitely to be due to nebulium. He was moreover able to predict the presence of a line which was afterwards found in a photographic spectrum by Wright. Dr. Nicholson has also shown that the radius of the atom of nebulium is 3·453 tenth-metres; a tenth-metre being the ten thousand millionth part of a metre.

Nebulium is not the only "unknown" gas in the universe. There is one part of the Sun's surroundings that we only see when the Sun is eclipsed—the Corona—a pearly-tinted glory that stretches out from the sun in irregular rays and petal-like forms to distances that are thousands or millions of miles beyond the chromosphere. The element or elements that constitute the corona, have not yet been identified on the Earth, but it gives a series of bright lines, the chief being one of wave-length 5303 in the green. Nicholson has been investigating this also, and though he has not yet published the nature of the atom whose vibrations give rise to this chief "**coronium**" line he has traced many other of the coronal lines to the atom of "**proto-fluorine**," that being the name he has given to the theoretical element whose atoms when neutral have five negatively charged electrons rotating in a plane circle round a positive unit whose charge is five times that of any one of the rotating electrons. This atom is rather larger than that of nebulium, having a radius of 5·802 tenth-

metres ; but the velocity of its electrons round the positive unit is 2·1 times greater than of the electrons of nebulium.

The spectrum of Nebulium, though the element itself is still unknown in terrestrial laboratories, first demonstrated the existence of true nebulæ in the depths of space.

CHAPTER XIII

SUMMARY

In the preceding chapters an attempt has been made to give a sketch of the chief results obtained by the application of the spectroscope to astronomy during the fifty years that have elapsed since Huggins entered the field. Few nowadays realise how small was the instrument with which he began his great work. His telescope indeed was a good one, having an object glass of 8 inches aperture made by Alvan Clark, but his first star spectroscope, every detail of which had to be thought out and designed by himself, had a collimator of only three-fifths of an inch aperture, and of $4\frac{1}{2}$ inches focal length. Yet after he had been at work only four years with this modest equipment, he was able in a lecture delivered before the British Association at Nottingham in 1866, to summarise the advances already made in the following terms.

1. All the brighter stars, at least, have a structure analogous to that of the sun.
2. The stars contain material elements common to the sun and earth.
3. The colours of the stars have their origin in the chemical constitution of the atmospheres which surround them.
4. The changes in brightness of some of the variable stars are attended with changes in the lines of absorption of their spectra.
5. The phenomena of the star in Corona appear to show that in this object at least great physical changes are in operation.
6. There exist in the heavens *true nebulæ*. These objects consist of luminous gas.

The Royal Society came to his assistance in 1870, and put at his disposal a fine equatorial carrying two

telescopes, one a refractor of 15 inches aperture, the other a Cassegrain reflector of 18 inches, and with these all his subsequent work was effected; the little spectroscope that he used at first being finally superseded by a fine 4-inch Rowland grating for ordinary work and a spectroscope with quartz lenses and iceland spar prism for taking photographs in the ultra-violet.

Dr. Huggins commenced his spectroscopic studies in collaboration with Dr. W. Allen Miller, but this association did not last long, as other duties claimed Dr. Miller's attention. For thirteen years Huggins laboured alone, but in 1875 he married Miss Margaret Lindsay Murray, who at once entered enthusiastically into her husband's studies and proved herself a most able and devoted assistant.

In 1891 he became President of the British Association, and his Presidential address at its Cardiff Meeting was devoted to carrying on the history of the development of prismatic astronomy during the quarter of a century which had elapsed since his former lecture. Six years later he contributed an historical note on the work carried out by his wife and himself to the *Nineteenth Century Review*, concluding: "We found the new astronomy newly born in a laboratory at Heidelberg; to astronomers she was

> . . . a stranger
> Born out of their dominions.

We take leave of her in the full beauty of a vigorous youth, receiving homage in nearly all the observatories of the world." In 1899 Sir William Huggins, as he had now become, brought out in conjunction with Lady Huggins, a magnificent *Atlas of Representative Stellar Spectra* with explanatory text, mainly devoted to the discussion of the "evolutional order of the stars and the interpretation of their spectra." In 1909 Sir William and Lady Huggins followed the *Atlas* by a second volume of the Publications of the Tulse Hill Observatory. This last was a collection of his scientific papers, and

marked the completion of his life-work. "These original observations," the Authors write in the Preface, "notwithstanding the serious drawbacks and limitations which must be present in pioneering work, have in their collected form all the interest of a nascent science, since they led directly to, and indeed themselves formed a not inconsiderable part of the foundations of, a new branch of Astronomy, which extends the chemistry and physics of the Earth to the heavenly bodies, and under the new name of Astrophysics, is to-day zealously cultivated in all the principal observatories of the world."

He still continued to take an active interest in all scientific progress. "Only a week before his death he took part in a meeting of a joint committee of the Royal and Royal Astronomical Societies for making arrangements for the publication of a collected edition of Sir William Herschel's papers, an undertaking due largely to his initiative. . . . His death, at the age of eighty-six, took place in a nursing home in London on May 12, 1910, unexpectedly, after one day's illness."[1]

In this little volume only the chief features of Huggins' researches, only the leading discoveries effected in astronomy by the spectroscope have been noticed; a few spectra only of those of the many elements have been described. More than this could not be accomplished in the space. Yet the author is fain to hope that some indication has been given of the chief result of this half-century of triumphant research, namely the testimony which the spectroscope has given to the essential unity of creation.

A given substance has its physical qualities. It may be hard, tough and heavy, or soft and light; dark in appearance or bright. These are its outward qualities. Next come its chemical affinities; it behaves in this or that manner when acted on by various reagents. But it has qualities more intimate still, more completely

[1] Obituary Notice, *Proceedings of the Royal Society*, Series A, Vol. 86, p. xix.

characteristic of it, because they are the qualities of its ultimate molecules and it is these qualities which give to each substance its appropriate spectrum.

For the lines of a spectrum are the evidence of the vibrations which the ultimate molecules of that element take up, to which they respond, and the wonderful intricacy which many of these spectra display has already yielded to analysis and been found to conform to a formula of a comparatively simple type, with its chief constant the same for all elements.

Turning from the ultimate molecule, an entity so small that it necessarily escapes our most powerful means of magnification to render it directly visible, to the enormous suns transcending this Earth of ours many millionfold in size, and the same testimony to unity is not less apparent. They reveal to the spectroscope the presence of the same elements; they are built on the same plan; their differences are but differences of size or age or development; they exhibit every possible gradation in one and the same series; the unity of the whole is manifest.

Astronomy is the oldest of the sciences; Astrophysics, that is to say, Spectroscopic Astronomy, is the youngest. Yet they concur in their Testimony. The Universe is One.

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